





Interim Report

I-A2049-16

# A BIBLIOGRAPHY (WITH ABSTRACTS) ON GAS-LUBRICATED BEARINGS - REVISED

*by*

A. Peters
E. B. Sciulli

*Edited by*

D. D. Fuller

October 15, 1961

*Prepared under*

Contract Nonr - 2342(00)
Task NR 061-113

*Jointly Supported by*

DEPARTMENT OF DEFENSE
ATOMIC ENERGY COMMISSION
MARITIME ADMINISTRATION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

*Administered by*

OFFICE OF NAVAL RESEARCH
Department of the Navy



THE FRANKLIN INSTITUTE
LABORATORIES FOR RESEARCH AND DEVELOPMENT
PHILADELPHIA PENNSYLVANIA

Interim Report I-A2049-16

# A BIBLIOGRAPHY (WITH ABSTRACTS) ON GAS-LUBRICATED BEARINGS - REVISED

*by*

A. Peters
E. B. Sciulli

*Edited by*

D. D. Fuller

October 15, 1961

*Prepared under*

Contract Nonr - 2342(00)
Task NR 061-113

*Jointly Supported by*

DEPARTMENT OF DEFENSE
ATOMIC ENERGY COMMISSION
MARITIME ADMINISTRATION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

*Administered by*

OFFICE OF NAVAL RESEARCH
Department of the Navy

CONTENTS

## INTRODUCTION

This bibliography was prepared ~~at the Franklin Institute Laboratories for Research and Development~~ under a program of research on gas-lubricated bearings supported jointly by agencies of the Department of Defense, Atomic Energy Commission, Maritime Administration and National Aeronautics and Space Administration and administered by the Office of Naval Research. Other technical reports issued under this program are listed in the Appendix.

This work is an expansion of the bibliography issued in September 1959 and contains 174 additional references. The references from the 1959 bibliography, Franklin Institute Laboratories Interim Report I-A2049-6, have been reproduced verbatim. Wherever possible a resumé in English of each reference is included. In most cases the abstracts were taken verbatim from the author, translation being made when required. When necessary or desirable, resumés were prepared or revised by FIL staff members.

Four indexes are provided in the Appendix for the convenience of the reader. Even though the bibliography in its entirety covers a rather specialized subject, the Subject Index subdivides the many varieties and types of gas-lubricated bearings. The Yearly, Patents and Corporate Name Indexes are self explanatory.

Every effort has been made to make this a comprehensive listing of all references published prior to July 1, 1961 which deal directly or indirectly with gas-lubricated bearings. The authors would be grateful if any omissions are called to their attention.

The compilation herein has resulted from the combined efforts of the SCIENCE INFORMATION SERVICE (SIS) of the Franklin Institute Library assisted by personnel of the Friction and Lubrication Laboratory. The authors wish to express their appreciation to all those who contributed bibliographies on gas bearings, called attention to new references, provided copies of difficult to obtain articles, or otherwise made their task easier.

1. ABBOTT, W. G., JR., "Gas-Lubricated Bearing," U. S. Patent 1 337 742, issued 1920.

The externally-pressurized gas bearing patented is designed with complementary tapering bearing surfaces. These could be conical bearing surfaces, spherical surfaces or other similar forms of bearing surface of which one member is convex and the other concave. The inventor claims that the bearing will withstand a much greater axial thrust or load and also a greater side pressure or side thrust than cylindrical and plane surfaces.

2. ABBOTT, W. G., JR., "Device for Utilizing Fluid Under Pressure for Lubricating Relatively Movable Elements," U. S. Patent 1 185 571, issued 1916.

The patent is for externally pressurized, gas-lubricated, rotating and reciprocating type bearings. For descriptive purposes, these devices are assumed to be used in a spinning mechanism such as is employed in the textile industry.

3. ADAMS, C. R., "The Step Bearing: A New Concept in Air Lubrication," Product Engineering, Vol. 29, No. 50, Design Issue Dec. 8, 1958.

Consisting of only two parts, bearings like the one described are rugged and inexpensive. They can be operated with air, gas water, or mercury at high or low temperatures and speeds. (Auth.)
These bearings are characterized by an extremely small sill length. The article itself appears to be rather sketchy with much information missing.

4. ADAMS, C. R., "Step Gas Bearings", SAE J. Vol. 68, No. 6, June 1960, pp. 54-57 under "New Gas Bearing Design Gives Increased Load Capacity")

An externally pressurized bearing developed by Boeing is described. This bearing throttles the gas as it leaves the bearing, rather than as it enters. Dams or steps machined on either the shaft or journal do the throttling and build up pressure. With a step on shaft or housing, pressure builds up under the shaft and creates lift. Since the flow rate through the gap at the top of the shaft is greater than the flow rate at the bottom, there is a greater pressure drop

at the top. This difference provides the lift necessary to float the shafts. It is claimed that such problems as shaft expansion due to centrifugal force, thermal expansion, and reduction of load-carrying capacity have been overcome. A series of pressure distribution tests starting with a simple setup to measure pressure along the top, bottom and two sides of a 2 inch diameter shaft in a stepped bearing block, were conducted It is reported that a number of failures occured because shafts and journals galled from metal-to-metal contact during starts, stops, and sometimes while running.

5. ADAMS, C. R., "Only the Best for Aircraft Accessories," Power Transm. Design, July 1961, pp. 38-39

This is a brief article which states in general terms that gas bearings have distinct advantages for aircraft accessories as air speed increases and the space allotted to these accessories decreases.

The need for sources of pressure for gas bearings in aircraft equipment are expressed. The author mentions a gas bearing developed by Boeing Airplane Co. It is stated that this gas bearing eliminates the standard orifices and pockets usually designed into these units. This bearing uses a double outer diameter on the shaft and a straight sleeve on the bearing surface - or a straight shaft with the bearing surface having two inner diameters. This stepped shaft localizes galling and prevents complete seizure if there is intermittent rubbing.

Gas is fed into the cavity between surfaces and bleeds out of the ends of the housing. Bearing effectiveness depends on the two clearances between the shaft and bearing to restrict flow and produce the pressure differential which floats the shaft.

The author states that, in this bearing, by avoiding orifices and pockets production cost is reduced and reliability is increased. Further, the gas need not be as clean as in other types because contamination is given a wide path for escape.

How to obtain a satisfactory shut down of a high speed gas bearing after loss of gas pressure is a question that still requires considerable development. The author suggests that this can be done by a special treatment of the surfaces of the shaft and bearing.

6. ADAMS, C.R., J. DWORSKI and E.M. SHOEMAKER, "Externally Pressurized Step Journal Bearings", ASME Preprint, Paper No. 61-LubS-8, May 1961, 8 p.

An externally pressurized gas journal bearing which achieves its load carrying capability by utilizing flow throttling dams parallel

to the direction of rotation is discussed in this paper. Test procedures and equipment used to develop this bearing concept are described. A theoretical method of determining pressure distribution and load carrying capacity for the bearing is presented and correlated with experimental data for non-rotating shafts. Experiments showing the behavior of the bearing under shaft whirl conditions are described and illustrated. Suggested ranges of the design parameters are indicated. The paper also points out advantages accruing from the design simplicity as well as the static and dynamic stability of this bearing concept. (Auth.)

7. "Air Bearing Levels Dividing Table," Product Engineering, Vol. 27, April, 1956, pp. 156-157.

Master code wheels for angle digitizers made by Baldwin Piano Company require angular graduations to an accuracy not attainable with mechanical dividing engines. Photographic, electronic and mechanical principles, combined in a machine with the dividing table leveled to one wavelength of light, produce the required accuracy. (Auth.)

The story, told in four pictures with titles, reveals that externally-pressurized air bearings made of glass were used in the system.

8. "Air Bearing Vibration Machine," Material Laboratory, New York, Brooklyn 1, N.Y., Technical Review 1956, pp. 4-7.

Mention is made of a device to help evaluate the mechanical characteristics of electron tubes and other equipment. This includes the mechanical reproductions of random noise excitation. For this purpose the test equipment (vibration machine) must have no resonances in the frequency band of interest and it must also meet other rather stringent conditions. It was found that a vibration machine incorporating air bearings could fulfill most, if not all the necessary requirements. (See SCHNEE).

9. "Air Bearings Support Lateral-Motion Vibration Tester", Design News Oct. 12, 1959. pp. 64-65

This article describes a vibration test system designed to handle components such as vacuum tubes, relays and small sub-assemblies throughout the entire audio spectrum. 400 watts of audio power produce approximately 50 lbs. of force over frequency range of 5 cps to 10kc. Total displacement is 0.5 inch with max. specimen weight of 5 This tester (LCM 100) is a product of the LCM Div. of L.C. Miller Co., Los Angeles, Calif.

10. "Air Lubricated Bearings - Some Pros and Cons About Them," Power Transmission Design, Vol. 1, No. 5, May 1959.

This article abstracts some of the material from Chapter 9 of the book, "Theory and Practice of Lubrication for Engineers,"

11. "Air Lubricates Grinder Head Bearing," Machine Design, Vol. 24, No. 6, June 1952, p. 138.

News item describing a small grinder that has air lubricated bearings. Built in two models, by Pratt and Whitney, the units have speed ranges from 35000 to 50000 rpm and 60000 to 100000 rpm. Air requirements range from 25 to 36 cfm.

12. "Air Lubricated Michell Bearing," Engineering, Vol. 116, No. 3007, Aug. 17, 1923, p. 203

Brief article mentioning that Kingsbury constructed a model air lubricated thrust bearing.

13. "Air Lubricated Thrust Bearing," Library of Congress, PB 117 333, (Appendix B.)

Included in a Materials Testing Report from NRL is an appendix containing mention of two air-lubricated bearings (6 and 8-inch diameter) which were used as part of the test equipment. No other information either experimental, theoretical, or design is given in this report.

14. "Air and Oil Invade Computer Field", Prod. Engng. Vol 32, No. 23, June 5, 1961, pp. 54-56

In newly developed electronic computers, the spacing of magnetic head to disk is maintained by the self-induced pressurized air film generated between the spinning disk and the slightly convex metal shoe into which the magnetic read and write head fits. Since the linear speed of the recording tracks, past the magnetic head, varies with their radial position on the disk, the constant applied load produces corresponding variations in bearing film pressure and head-disk spacing. These variations maintain the same total recording capacity on each track on the disk, while surface speeds range from 1200 to 2100 ips and spacing from 250 to 350 microinches.

15. "Air Replaces Oil for Bearing Lubrication," Aminco Laboratory News, Sept. 1958, p. 10.

This is a short, 200 word, news item which notes that many gases can be used as lubricants in either self-acting (hydrodynamic) or externally-pressurized (hydrostatic) bearing applications.

16. "Air Stream Sets Spacing in Film-disk Memories," Machine Design, May 25, 1961, p. 8.

"Bernoulli Disks" memories, so called because of the fluid-motion principles involved in designing for head-to-tape gap, are briefly described.

When the disk is spinning, centrifugal forces coupled with the hydrodynamic forces of an air stream maintain a 1-mil gap between disk and heads. Laboratory for Electronics Inc., which developed the device claims immunity from shock and vibration, among other advantages.

17. ALLEN, D.S., P.J. STOKES and S. WHITLEY, "The Performance of Externally Pressurized Bearings using Simple Orifice Restrictors". Trans. ASLE Vol. 4, No. 1, April 1961 pp. 181-196

The load capacity and vibration characteristics of externally pressurized thrust and journal bearings have been investigated. The bearings used orifices sufficiently recessed back from the bearing surface to ensure that the area of the orifice is the minimum presented to the gas flow. The journal bearings consist of plain cylinders with one or two rows of eight orifices, and the thrust plates consist of plain discs with six orifices drilled in equispaced circumferential grooves.

The load capacity of the thrust plates agrees with that calculated but the vibrations are greater than predicted. The load capacity of the journal bearings is about half that calculated assuming axial flow conditions in the bearing, but circumferential flow can account for the difference. Synchronous and half-speed vibrations of a shaft rotating within these bearings have been measured and found to agree with those calculated on the assumption that the gas films behave as linear springs. (Auth.)

18. "An Air Thrust Bearing," Mill and Factory, Vol. 54, No. 3, Mar. 1154, p. 139.

Short article on the use of an air lubricated thrust bearing. (Same device discussed in "Cushion of Air Serves as Thrust Bearing.)

19. ANNEN, R., "Fluid Support Bearing," U. S. Patent 2 684 272. issued 1954.

The object of this invention is to provide a bearing of the fluid supported type (externally pressurized) wherein the automatic centering of the movable body is improved. In the journal bearing version, inclined spring-like fingers form the axial extremities of the pressure chambers. When the chamber pressure increases the fingers move outward cutting down the effective area through which the fluid can flow. Conversely, a shaft displacement causes some "leakage" areas to become smaller, choking off part of the flow and permitting chamber pressure to build up. Meanwhile, diametrically opposite, the escape area and flow increase and result in a lowering of chamber pressure. The response of the system is said to be so rapid that an immediate, automatic "centering" of the journal is achieved.

20. ARMSTRONG-SIDDELEY, "Gas Bearing Applications," Reactor Component Division, Armstrong Siddeley Motors Ltd., Coventry, England, Feb. 1958.

Advertising literature of a commercial device (gas pump) which employs gas lubricated bearings.

21. ARTOBOLENSKI, I. I., S. A. SCHEINBERG, "High Speed Sliding Bearing Using Air as a Lubricant," (In Russian) Machine Construction Newsletter, No. 8, U.S.S.R. 1950, pp. 5-12.

The following items are covered in separate chapters;
1. Principles governing aerodynamic bearings.
2. Structure of a supercentrifuge and its basic elements.
3. Method of designing bearings.
4. Basic properties of gaseous lubricants.

Conclusion: The main application of gas bearings is in cases of high speeds of revolution. It is difficult to define speed limits for these devices; while light loads can be supported at lower speeds, the higher rpm limit is generally set by the strength of the material or stability of the rotor.

Because of the availability of lubricant (air) and the possibility of operating at higher speeds, there promises to be numerous applications of gas bearings. (Auth.)

22. ASHMEAD, G.B., "Let Air Do the Work," Mechanix Illustrated, Vol. 54, No. 4, April 1961, pp. 92-93.

This is a news item on a new cargo handling system, which was developed by the Douglas Aircraft Co. Called "Glide-Aire", the system works using either of two methods.
1. The air-in-floor method consists of a compartmented floor fitted with a chamber of air under pressure (an air plenum chamber). The floor has spaced, ball air valves which protrude slightly above the surface. The heavy load depresses the ball valves and the escaping air provides a thin cushion of air under the load. The ball valves are closed by spring loading which shuts off the air when the load is removed.
2. In the air-in-pallet method, the cargo-handling pallet has an air plenum chamber built into it. The air is supplied from a shop line or mobile air supply. The pallet is equipped with resilient discs on the bottom, through the center of which the air is forced out. It is claimed that loads from 100 lbs to 7 tons have been moved on cushions of air with 1 to 35 lbs per square inch of pressures.

23. "A Two-Axis Gas Bearing Gyroscope," Quart. Rept. No. 1, Kearfott Co., Inc., Little Falls, N.J., 12 June-15 Sept. 59, 28 Sept. 59, 45 p. Rept. No. M-1999-4-1 Contract NOa(s) 59-6218-c, AD-251 033L

A preliminary gyro design was established and detailed. A spin motor capable of producing torque about the spin axis only, and independent of the angular position of the rotor relative to the stator was investigated. Analyses indicate that a split stator arrangement of the proper geometry would satisfy the conditions of the problem.

Tests were performed to determine the torque effects due to a simulated gyro wheel spinning inclined to a flat plate. These were evaluated and an expression was derived for the pressure effect. Fabrication of gyro parts was initiated, special attention being given to the gas bearing parts. New methods of fabricating and plating these are being investigated. (Auth.)

24. "A Two-Axis Gas Bearing Gyroscope," Quart. Rept. No. 2, Kearfott Co., Inc., Little Falls, N.J. 15 Sept.-15 Dec. 1959, 28 Dec. 59, 16 p. Rept. No. M-1999-4-2 Contract No a(s) 59-6218-c. AD-251 o34L

A pre-prototype gyro motor was designed and built, and a test fixture was fabricated to evaluate motor performance. Substantial improvements were made in the fabrication of gas bearings. The first prototype gas bearings were levitated successfully and evaluation tests are in progress. A two-axis test table designed especially for the evaluation of the gas bearing gyro was fabricated and assembled. (Auth.)

25. "A Two-Axis Gas Bearing Syroscope", Quart. Rept. No. 3, Kearfott Co., Inc., Little Falls, N.J., 15 Dec. 59-15 Mar. 60, 23 Mar. 60, 10 p. ,Report No. M 1999-4-3 Contract NOa-(s) 59-6218-c. AD-251 o35L

The pre-prototype gas bearing gyro was assembled and tested on a specially designed two-axis test stand. The results obtained, although preliminary in nature, provided important information on the performance of prime gyro components such as pickoff, torquer and gyro motor. Improved lapping techniques aided gas bearing fabrication. The first pocketed gas bearing was made successfully. Evaluation of the prototype gas bearings continued and essential operational information was obtained. (Auth.)

26. "A Two-Axis Gas Bearing Gyroscope," Quart. Rept. No. 4, Kearfott Co., Inc., Little Falls, N.J., 15 Mar.-15 June 60, 27 June 60, 6 p. Rept. No. M-1999-4-4, Contract NOa(s) 59-6218-c, AD-251 036L

The engineering efforts were concentrated on the testing and analysis of the prototype gyro motor. Three types of spurious torques, namely, permeance, magnetic hysteresis, and magnetic axis deviation, were investigated to determine methods which will lead to the elimination of their effects on the gyro. The test results obtained provided valuable information as to the mechanisms which give rise to these torques. (Auth.)

27. "A Two-Axis Gas Bearing Gyroscope," Quart. Rept. No. 5, Kearfott Co., Inc., Little Falls, N.J., 15 June - Sept. 60, 12 Oct. 60, 12 p. Rept. No. M-1999-4-5. Contract NOa-(s) 59-6218-c, AD-251 037L

The engineering efforts were concentrated on the study and analysis of spurious torques generated by the hysteresis driving motor. Several torque compensation schemes were tested and evaluated. The results of these tests demonstrated that the motor restraining torque can be compensated. (Auth.)

28. "A Two-Axis Gas Bearing Syroscope", Quart. Rept. No. 6, Kearfott Co., Inc., Little Falls, N. J., 15 Sept. - 15 Dec. 1960, 31 Jan. 1961, 13 p. Rept. No. M-1999-4-6, Contract No. a(s)59-6218-c, AD-252 685

The study, testing, and analysis of torques which tended to restrain the gyro wheel from acting as a free-spinning rotor were conducted. These torques were designated as quadrature and inphase spring torques. Tests were performed on a re-worked gyro rotor to determine the magnitude and origin of these torque vectors. The restraint vectors were analyzed and a gyro with an optimum configuration was assembled for drift tests. (Auth.)

29. AUSMAN, J. S., M. WILDMANN, "How to Design Hydrodynamic Gas Bearings," Product Engineering 28, No. 25, 1957, pp. 103-106.

The fundamental principles of hydrodynamic gas bearings are discussed. Charts and equations are given for designing a hydrodynamic gas bearing.

30. AUSMAN, J. S., "The Finite Gas Lubricated Journal Bearing," Paper 22, Hydrodynamic Lubrication, Conference on Lubrication and Wear, London, 1st-3rd Oct. 1957, The Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W. 1.

A first-order perturbation solution is obtained for hydrodynamic, gas-lubricated, journal bearings of finite width. It permits determination of end-flow factors on bearings operating at small eccentricity ratios. In comparisons with experimental data, it is shown that these end-flow factors may be used with Katto and Soda's infinite-width journal bearing solution to predict load-eccentricity characteristics on actual bearings. The agreement with experimental data is better when an adiabatic rather than an isothermal pressure-density relationship is assumed. (Auth.)

This is an extension of the author's previous work. Here again third order terms are not included in the solution (see Wildman) and the question of convergence is not investigated.

The agreement of the experimental results of other authors with these theoretical adiabatic curves is remarkably good. If this agreement is a true relationship and the agreement is enhanced by the "end flow factors" being added to Katto and Soda's solution, then the author has made a significant contribution to the gas bearing field.

31. AUSMAN, J. S., "The Fluid Dynamic Theory of Gas Lubricated Bearings," Trans. ASME, Vol. 79, No. 6, Aug. 1957 pp. 1218-1224.

A differential equation for the pressure distribution in gas-lubricated slider bearings is derived from the basic equations of fluid mechanics. The equation is an extension of Harrison's gas-bearing equation in that the infinite width and isothermal restrictions have been removed. A perturbation solution is proposed and is carried out for the special case of an infinitely wide, self-lubricating (hydrodynamic) journal bearing. Comparisons with numerical solutions to Harrison's equation indicate that the first three terms in the series solution are sufficient to determine the pressure distribution and bearing load with reasonable accuracy. (Auth.)

The author's approach, making use of a series solution for a differential equation is by no means unique in mathematics. Yet, the application of it to the equations of hydrodynamic lubrication with compressible fluids has attracted considerable attention.

In this paper the question of convergence of the series solution for the pressure distribution was not considered and only the first three terms of the series were used; that is, terms of third order and higher were neglected. The expression for load-carrying capacity is said to give good results for eccentricity ratios of 1/2 or less, but greater accuracy can be obtained and higher values of eccentricity employed if additional terms are used in the proposed solution.

The author's curves of theoretical pressure distribution, radial stiffness and angle between load and deflection appear to be in good quantitive agreement with the curves obtained from Harrison's work.

32. AUSMAN, J. S. "Theory and Design of Self-Acting Gas-Lubricated Journal Bearings Including Misalignment Effects." First Intern. Symp. Gas-Lubricated Bearings, Washington, D.C., Oct. 26-28, 1959, pp. 161-192.

Existing methods of analyzing self-acting, gas-lubricated journal bearings are reviewed briefly and discussed. Their results are compared with published experimental data. Two design approaches are then suggested: one, a simple approximate method to obtain a "first cut" or initial design, and the second, a more detailed procedure to refine the initial design.

33. AUSMAN, J. S., "An Approximate Analytical Solution for Self-Acting Gas Lubrication of Stepped Sector Thrust Bearings" ASLE Preprint, Paper No. 61-AM 5B-1, April 1961, 24 p.

Certain approximations are made which permit linearization of pressure (Reynolds) equation for compressible lubrication as well as the separation of variables. A series solution to the resulting approximate equation is then developed to obtain estimates of the pressure and load for self-acting stepped sector thrust bearings. Numerical solutions are presented showing the optimum number of sectors, the optimum step location, and the optimum depth of the step to achieve maximum load carrying capacities. A design chart permits rapid estimation of the load deflection characteristics for optimized stepped-sector thrust bearings covering a wide range of nominal operating conditions. (Auth.)

34. AUSMANN, J. S., "Torque Produced by Misalignment of Hydrodynamic Gas Lubricated Journal Bearings," Trans. ASME - J. Basic Engineering Vol. 82, Series D, No. 2, June 1960, pp. 335-341.

A perturbation analysis is used to find the angular displacement of a torque-loaded journal. Results are presented graphically in terms of non-dimensional parameters. A numerical example gives a misalignment torque of 0.16 lbs inches/sec. arc misalignment. This compares favorably with similarly sized pre-loaded ball bearings for gyroscope rotors. (Auth.)

35. AUSMANN, J. S., "An Improved Analytical Solution for Self-Acting, Gas Lubricated Journal Bearings of Finite Length," Trans. ASME - J. Basic Engng. Vol. 83, Series D. No. 2, June 1961, pp. 188-194.

An improved analytical solution designated the "linearized ph" solution is obtained for gas-lubricated journal bearings of finite length. Whereas the older, first-order perturbation solution is useful for small eccentricity ratios ($\varepsilon < 1/2$), the linearized ph solution may be used for high eccentricity ratios. As such, it permits estimation of ultimate bearing load capacity. The linearized ph solution is expressed in the form of simple corrections to the first order perturbation solution, and as such can be computed quickly and easily. (Auth.)

36. "Balancing Fixture Pivots on Air", Mach. Design, July 7, 1960, p. 130.

A completely automatic model produced by General Motors is described. An air bearing provides a low friction, sensitive pivot for a static balancing device. Unbalance is sensed as variation in magnetic reluctance between the tube and each of 4 walls of an electromagnet. Electronic read-out produces two signals from this information, one indicates angle of position of heavy side (or large side), the other, the amount of unbalance. Light side of brake-drum, assembly is indexed to work the welding units which apply additional material automatically proportioned by the read-out unit.

37. BARBEZAT, A., "Device to Balance Thrust in Turbines," U. S. Patent 1 030 153, issued 1912.

Dummy piston device which employs steam to balance the thrust load in a turbine.

38. BARD, D. O., R. FELTS, and H. McKENNEY, "Development of an Oriented-Wedge Air Bearing." Chrysler Corp. Missile Div., Detroit, Mich., Tech. Rept. RL-RI, May 1960, 82 p. ASTIA NO. AD-247 655

The report presents pertinent designs, experimental data, and performance results for a number of experimental, oriented-wedge, hydrodynamic, air-lubricated bearings for potential application to a gyroscope. The bearings are self-centering, require no preloading, and have almost unlimited life. In addition, the bearings should be capable of sustained operation at speeds in excess of 20,000 rpm, withstand up to 10 g radial and thrust load while in operation and 20 g in a non-operating mode, with a rotor weight of not more than 2 lbs.

The two wedge, 60° tapered-end plate bearing performed satisfactorily under a 13.3 g radial load, 3.2 g thrust load, at 24,000 rpm. Extrapolation of tests data indicates that maximum load capability is 40 lbs. (20 g, radial load). The two-wedge housing, 60° tapered-end plate bearing configuration, performed better than any other bearing configuration when an unbalanced rotor was used with it.

The two wedge, 60° tapered-end plate bearing experienced no metal-to-metal contact throughout a complete 180° position rotation at 24,000 rpm. All bearings performed better when the rotor unbalance was less than 800 micro-inch ounces.

Half-frequency whirl vibration, bending resonance and torsional frequency were too high to contribute instabilities on all bearing design concepts. One thousand stop-and-start, wear cycles caused no detrimental effects on bearing performance under a one g loading condition.

Bearing surface finishes varied from 4 to 15 micro-inches. However, no noticeable influence on performance could be detected in this range. Although complete evaluation could not be made of the three-wedge housing, flat three-wedge and bearing configuration, this configuration shows promise of good performance.

39. BARRANGON, M., "Behind the Scenes of the Space Age: Gas Bearing", Mech. Engng., Vol. 83, No. 7 July, 1961, p. 64

A brief note which accompanies a photo-picture of a gas bearing developed by Boeing, Seattle. It states that this bearing operates at such low temperatures that the nitrogen-gas lubricant becomes liquid. It can also operate at high temperatures. The temperature range is from-330 to +600F. This is a step bearing in which a slight recess in the bearing shaft receives the pressurized gas which lifts the shaft and becomes the lubricant. The gas flow is throttled as it escapes from the recess. Speeds: up to 100,000 rpm, have been reported.

40. BARRICK, P. L., J. A. BRENNAN, D. B. CHELTON, K. B. MARTIN, "Literature Survey of Bearings, Friction, Wear and Lubrication Pertinent to Cryogenic Applications," NBS Report 6018 Unpublished, NBS Boulder Laboratories, Boulder, Colo.

Since this report is unpublished it is not generally available. However, only Section 2.2 "Gas Lubrication" is of interest and all applicable references from that source are included in this bibliography.

41. BARWELL, F. T., "Lubrication of Bearings," Butterworths Scientific Publications, London, 1950. "Air Lubrication," pp. 113, 222-225.

Contains only a brief mention of the use of air as a lubricant. Cites Gerard and Shires.

42. BATES, M. F., "Resetting Means for Air Borne Gyroscopes," U. S. Patent 2 200 976, issued 1940.

Air under pressure is used to float the casing of a gyroscope so that it can oscillate about a horizontal axis.

43. BEAMS, J. W., "High Rotational Speeds," Journal Applied Physics, Vol. 8, 1937, pp. 797-804.

The paper contains a rather impressive list of references which deal primarily with centrifuges. The discussion which follows includes the abstract of this paper and also most of those it references.

It appears that following the work of Henriot and Huguenard it became possible to produce relatively low cost centrifuges which made use of an air-driven turbine and air-lubricated bearings. However, the centrifuge has since evolved into an electrically driven rotor with bearings that use lubricants other than gases.

In the centrifuge literature, the theoretical aspects of gas bearing design is conspicuous by its absence and one senses that the bearings were built mostly by "cut and try." If any formal design methods were applied to the bearings of these centrifuges, details of them have either not come to light or have not been published. There is some mention made of the design of the turbine rotor and nozzles and the relative angles between them, but the amount of information given is rather limited.

44. "Bearing Means for Supporting Machine Elements", Great Britain Patent 856,543, Dec. 1960.

The invention refers to bearing means for supporting machine elements, such as slides or shafts or tool spindle of a horizontal boring machine and includes a bearing member having a micro-porous bearing surface and means for forcing air with oil fog through these pores. The air bearings consist of tapered porous metal bushes through which air is forced under pressure. Means for adjusting the clearance in this bearing are provided.

45. BECKER, H. I., "Air Bearing Graphite Lining (porous)," U. S. Patent 2 627 443, issued 1953.

The subject of this patent is an oil free, porous, graphitized, sleeve bearing which uses externally pressurized gas as a lubricant. The advantages of this bearing stem from the low frictional characteristics of the carbon material.

46. BECKER, H. I., "Air Bearing Graphite Lining (porous)," U. S. Patent 2 645 534, issued 1953.

An externally-pressurized bearing is described. In this device the gas is distributed inside a hollow metal chamber to the outer side of a porous, graphitized carbon liner (bearing) through which it passes and acts to support the load. Applications shown include journal bearings and cup (spherical seat) bearings of various design and use.

47. BIBBINS, R. E., "Compass," U. S. Patent 1 385 423, issued 1921.

A compass which comprises a base cup adapted to permit a supply of air to pass therethrough to the chamber of said cup, a floating vessel adapted and shaped to rest in said base cup when stationary and to float therein when raised by the supporting air, a removable and adjustable cover for said vessel, and a ball adapted to be located inside said vessel when covered and to spin freely and effectively therein when, and as, acted upon by the air fed to said vessel through said base cup. (Official Gazette)

48. BIDWELL, E. C., "Work Holding and Clamping Mechanism for centerless Grinding Machines," U. S. Patent 2 754 641, issued 1956.

This invention provides means for holding a work piece clamped against a rotating driver, such means comprising a piston movable in one axial direction to clamp the work piece and in the

opposite direction to unclamp the work piece, and inside the piston a rotable work clamping member, and utilizing fluid (gas) pressure to form thrust and journal bearings between the piston and member with means independent of the journal bearing function for controlling the thrust bearing pressure so as to clamp the work piece or permit its release as by spring means. (Auth.)

49. BILD, C. F., P. F. VIAL, "A Simple High-Speed Air Spinner for Centrifugal Testing of Small Mechanical Devices," Trans. ASME, Vol. 75, May, 1953 pp. 515-519. Discussion by O. C. Brewster.

A centrifuge was developed for the purpose of testing the functioning of mechanical and electromechanical devices while these devices were spinning up to 100 rps. A typical device is a clock mechanism, in which parts of considerable mass shift position during test.

The discussion of the paper by Brewster is considered by many to be of great interest.

50. BLIZARD, R. B., "Bearing," U. S. Patent 2 695 199, issued 1954.

A bearing open at one side comprising interfitting surfaces, means for supplying lubricant under pressure between said surfaces at spaced regions, and suction means for withdrawing lubricant therefrom at a point opposite said open side and intermediate the points of introduction of said pressure lubricant. (Official Gazette)

51. BLOKH, E. L., "Techenie Vlazkogo Gaza Dvumia Dvizhushchimisia Parallel'nymitsilindricheskimi Poverkhnostiami Proizvol'noi Formi (Study of the Flow of Viscous Gas Between Two Parallel Cylindrical Surfaces of Arbitrary Form)," Prike. Mat. i Mekh. 1956, pp. 116-119.

Study of the flow of viscous gas between two parallel cylindrical surfaces of arbitrary form. The motion of gas is assumed to be caused by the rotation of the surfaces of which the inner is taken to be stationary. It is shown that for this type of motion, the ratio of the forces of resistance for viscous gas and viscous fluid is not affected by the configuration of the cross section of cylinders. Two numerical examples considered include the flow of viscous gas between two parallel planes and the flow between two co-focal elliptical cylinders. (Review—AERONAUTICAL ENGINEERING - 1956).

This paper was not available for review. It is possible that this paper is not related to gas lubricant bearings.

52. BOEKER, G., D. D. FULLER, C. F. KAYAN, "Gas Lubricated Bearings, A Critical Survey," WADC Technical Report 58-495. ASTIA No. AD 216 356. Also available through Office of Technical Services.

The authors, in this report, take a long critical look into some of the literature on gas bearings. The work is broken down into three parts as follows:

Part 1 - "General Hydrodynamic Theory and Hydrodynamic or Self-Acting Bearings,"

The purpose of Part 1 of this report is to summarize the work on the hydrodynamic types of gas-lubricated thrust and journal bearings with their attendant problems such as self-excited shaft vibrations.

In the belief that a measure of skepticism is a real stimulant to progress, the author has adopted such an attitude towards some of this work.

Part 2 - "Air Lubricated Hydrostatic or Externally - Pressurized Bearings,"

The literature on externally-pressurized bearings is critically reviewed. An effort has been made to present a broad picture of what is known in terms of analysis, design and performance of these bearings. Emphasis has been given to those areas where further information is definitely needed.

Part 3 - "Feasibility Study on the Determination of Pressure Distribution in Hydrostatic Gas - Flow Bearings via Electrical Analogy,"

The purpose of this part of the report is to investigate the feasibility of representing the gas-flow through the various components of a gas-lubricated bearing by means of a simulation electrical analogy circuit, such that at various points throughout the system, pressures may be determined by the analogy method, thus on this basis making prediction of bearing performance possible. Inasmuch as the objective is to explore the possibilities of a practical procedure, the proposal utilizes characteristic and representative flow relationships, whose form necessarily dictate the requirements of a solution.

53. BOLSTER, W., "Multiple Gyro Air Borne Compass," U. S. Patent 2 262 232, issued 1941.

Complementary spherical members separated on air film for universally supporting a central sphere for turning about a vertical axis and oscillating about both horizontal axes. Appropriate passages are employed for suppling air.

54. BOSCO, A., E. S. CAIN and G. L. GREEN, "Exploration of Bearing Lubrication Using Working Fluid Vapors," AiResearch Manufacturing Co. of Arizona, Tech. Report No. BR-5213-R, April 1 - July 15, 1961, Aeronautical Systems Div. Progress Report No. 1, July 1961, USAF Contract No. AF 33(616)-8082; 30p.

The principal objective of this program is to investigate the lubricating characteristics of potassium and rubidium vapors in pneumostatic (externally pressurized) and pneumodynamic (self acting) thrust bearings at conditions representative of typical closed-cycle space power units.

Preliminary thrust bearing analyses were made to determine the test rig requirements of flow, pressure, and general test bearing environmental conditions. The test rig and loop layout and detail drawings have been made. Special test instrumentation designs have been initiated, and feasibility checks are under way. Final analysis of the pneumodynamic tapered-pad thrust bearing has been undertaken and will be the first bearing type to be tested. (Auth.)

55. BOTTLE, D. W., "Note on an Air Supported Bearing," Royal Aircraft Establishment, Aero. Tech. Memo No. 6, 1948.

(Paper not available for review as of July 1, 1959.)

56. BOYD, G. A., "Oil Burner," U. S. Patent 2 177 053, issued 1939.

The patent is for a new fuel burner comprising a rotor having a coaxially disposed cup therein for receiving fuel to be atomized by centrifugal force and is particularly characterized by the fact that the rotor is entirely supported on a film of air during normal operation thus eliminating metallic friction. (Auth.)

57. BRADSHAW, B. and E. M. LOVE, "The Normal Impingement of a Circular Air Jet on a Flat Surface," Aeronautical Research Council, F.M. 2856, P.L. 20, Sept. 1959, 13 p.

Measurements of velocity magnitude and direction, static pressure, and skin friction have been made in a circular turbulent jet impinging normally on a flat surface. The speed in the jet just before impingement was 135 ft/sec. and its radius was about 2.5 inch. The region of increased static pressure near the stagnation point is roughly hemispherical, with a radius slightly larger than that of the jets. The maximum value of skin friction occurs at a radius approximately equal to that of the jet and is about 0.006 of the jet maximum dynamic pressure at the test Reynolds number. The virtual origin of the resulting radial wall jet is very close to the stagnation point. (Auth.)

58. BRAY, K.A. and W. McNOCHER, "Gas Bearings," Great Britain Pat. 873,412 July 26, 1961, 4 p.

This invention relates in particular to gas lubricated thrust bearings and to the dissipation of heat and prevention of distortion in such bearings.

The preferred method of achieving this is by fixing a thin disc closely behind the rear face of the rotating thrust plate remote from the bearing surface. Some of the ambient gas is entrapped in the narrow space between the disc and the rotating thrust plate. The trapped gas acts as insulation, so that a greatly reduced amount of heat is transferred axially from the bearing surface through the body of the rotating thrust plate to the remote rear face. Consequently almost all the heat is transferred radially toward the periphery of the rotating thrust plate whence it is dissipated to the containment vessel walls.

According to this, the order of distortion is reduced to a level far below that obtained when no insulation is provided.

This device is claimed to be particularly effective near the periphery where the radial conduction path is short, since the worst heat generation and consequent distortion occur at the largest radius.

59. BREHM, P., "Gas Bearings. Part III of the Hydrodynamic Type," Engng. News, Vol. 7, No. 3, May 1961, pp. 2-5

Part I of this series on gas bearings covered the features and theory of operation of hydrostatic or externally-pressurized gas bearings. The second category of gas bearings - hydrodynamic or self-acting types - have also been receiving considerable attention, mainly because of their unique suitability for space instrumentation such as in gyro spin motors. Part III describes the hydrodynamic type. The hydrodynamic bearing does not need an external gas supply; it generates and maintains its own gas supply as the shaft rotates within its bearings. As the shaft is caused to rotate, sliding friction of the shaft-journal surfaces is at first present; the shaft immediately assumes a very slightly eccentric position within the bearing and becomes supported by the first components of the hydrodynamic gas "wedge". The action here is analogous to that in a full-film or hydrodynamic oil bearing as described by the classic Sommerfield equations, except that we have the added complication of a compressible media, making theoretical analysis and prediction of performance somewhat more difficult.

Hydrostatic bearings and hydrodynamic bearings are compared as to their advantages and disadvantages, and each individual application is analyzed in terms of operating conditions.

60. BREWER, A. F., "Gaseous Lubrication," Lubrication Engineering, Vol. 13, No. 4, Apr. 1957, p. 189.

Brief article on use of gases as lubricants.

61. BREWSTER, O. C., "High Speed Rotor Using Gas-Lubricated Bearings to Get Away From Whip," U. S. Patent 2 603 539, issued 1952.

As a means for minimizing whip in a high speed rotor using gas-lubricated bearings, the inventor recommends the introduction of a lateral gas pressure on the rotor at one side of its axis. The patent is issued for the rotor.

62. BRIX, V. H., "Shaft Stability in Gas Film Bearings," Engineering 187, Feb. 6, 1959, pp. 178-182.

The author, discussing self-acting bearings, notes that they have an inherent weakness manifested in a tendency to cause the shaft to "whirl" or to precess bodily within the bearing clearance, thus making them greatly sensitive to unbalance and dynamic disturbances of various kinds. In this work he describes the results of tests made, not to change designs, but to control the manufacturirg parameters so as to make the best of the existing scheme. Experimental results on whirl are given in the form of curves.

63. BRIX, V. H., "Synchronous Whirling of Shafts in Plain (Gas) Bearings," IGR-R.C.A. 176, IGR-RB/R-261, 18 June 1956, United Kingdom Atomic Energy Authority, Capenhurst Works, Chester, England.

The report begins with a dynamical theory of a shaft vibrating in two bearings, paying special attention to the values of bearing film stiffnesses and their linearity.

Several experiments are then described, which were drawn from a fairly comprehensive investigation of the whirling problem and the collateral question of balancing.

The theoretical analysis is then applied to the experimental results with a fair amount of agreement in many cases. A further theoretical estimate, extended to the case of a shaft in an oil lubricated gearbox which was known to whirl, adds some more evidence of the possible usefulness of the approach.

The report concludes by illustrating several shaft-assemblies with their comparative lowest critical whirling speeds, as estimated by the formulae developed. (Auth.)

Since the question of dynamic instability in bearings increases in importance as rotational speeds increase, the author's report should be of great interest. The term "half-speed whirl" is

probably familiar to many readers but this is only one of many types of instability which have now been separately identified. The author makes a theoretical analysis of simple (cylindrical) synchronous whirl and conical synchronous whirl. Experimental tests are discussed and the results compared with the theoretical ones. Suggestions are made on steps to take to reduce synchronous whirl to a minimum.

64. BRODY, S., "Solution of Reynolds' Equation for a Plane Slider Bearing of Finite Width with an Isothermal Gas Flow," ASLE Preprint, Paper No. 60 AM 5A-4, April 1960, 21 p.

The designer of an air-slider requires accurate information on the load, center of pressure, and friction factors. A search of the literature showed that there is a need for more extensive solutions of Reynolds' equation, in the form of numerical values that are accessible and useful to the designer. This paper presents the numerical values, obtained by using a 704 computer, of the load, center of pressure, and friction factors for a plane inclined slider bearing with a gas film. These values are presented in tabular form for various slenderness ratios of slider vs. film thickness ratios. The resulting tables offer a simplified approach to the design of slider bearings and are applicable whenever certain conditions (laminar viscous flow, constant viscosity, etc.) are also met. A typical problem illustrating the use of the information contained in the tables is included. (Auth.)

65. BROWN, E. C., "Development of a High Efficiency, Air Lubricated Journal Bearing," Royal Aircraft Establishment Tech. Note Aero. 2107, June 1951.

Modifications to the air lubricated drag and side-force bearings of the virtual center balance in the R.A.E., No. 2, 11-1/2 x 8-1/2 ft., wind tunnel have resulted in a very substantial increase in their load carrying capacity. A total of eight bearings were affected and all are now working at load coefficients (Maximum load carried) (Projected area of bearing) x (Air supply pressure)) of between 0.77 and 0.86 compared with normally accepted values of 0.3 - 0.4 for this type of bearing. (Auth.)

An appendix contains some suggestions for the applications of the principles involved to the design of complete journal bearings.

Journal bearings, ($180^{0}$), air lubricated by a series of jets distributed mainly on the periphery and center line of the bearings, were modified and their load carrying capacity increased. The modification consisted of (1) lapping the mating surfaces to

improve the finish and cutting down the clearances and (2) forming a shallow cavity in the outer shell of the bearings. The cavity covered an area within the boundaries of the outer ring of jets and was "ventilated" (Pressurized) through the existing jets on the center line.

66. BRUBACH, H. F., "Some Laboratory Applications of the Low Friction Properties of the Dry Hypodermic Syringe," The Review of Scientific Instruments, Vol. 18, May 1947, pp. 363-366.

The principle of rotating either the barrel or plunger of a dry hypodermic syringe to produce a low friction gas lubricated bearing is described. The application of this principle to accurate measurement of gas volume at very low pressure heads, and further applications to other instruments operating at low pressure heads is indicated. Horizontal motion of the plunger was produced in a rotating syringe barrel with pressures as low as 0.6 dynes per $cm^2$. (Auth.)

This paper awakens one to a possible source and the relatively low cost of this type of device that can be used as a precision air bearing. The applications that were made of these syringes appear to be practical as well as novel. No theoretical treatment is given for the bearing described.

67. BRUGGER, R. G., "Air Bearing," U. S. Patent 2 695 198, issued 1954.

The invention is a "push-pull" type of bearing which may be used in devices such as gyroscopes. As designed it eliminates the need for "opposed" bearings. The method used is similar in a sense to that used by Gerard. In Gerard's invention, oil drawn from one chamber is pressurized and used in another chamber to support the load.

Here the fluid used is a gas and all the chambers or pockets are on one end or side of the bearing. The loadcarrying pockets are pressurized as before but the "sump" chamber is evacuated. The resulting pressure differential acts to hold the surfaces from separating. This restriction to motion has the same effect as the "opposite bearing." By proper balancing of sizes and pressures it should be possible to achieve a stiff bearing if desired.

68. BRUNNER, R. K., J. M. HARKER, K. E. HAUGHTON, A. G. OSTERLUND, "A Gas Film Lubrication Study, Part III: Experimental Investigation of Pivoted Slider Bearings," IBM Journal of Research and Development, Vol. 3, No. 3, July 1959, pp. 260-274.

The results of experimental measurements on pivoted slider bearings are presented, the experimental methods are described, and the experimental data is compared with data obtained from a numerical solution of the Reynolds differential equation for a compressible fluid. (Auth.)

See W. A. Gross and W. A. Michael for other papers in this group.

69. BRUNZEL, N., "Pressure Lubricating Bearing," U. S. Patent 2 756 114, issued 1956.

Externally pressurized gas-lubricated bearings are described in this patent. Suggested uses are in ultra centrifuges. It is also pointed out that these bearings do not require extended periods of relative motion between parts so that they can be used for "to and fro" movements such as occur in compressor pistons, regulating valve shafts, and the like.

70. BRUNZEL, N., "Druckluftgeschmierte Gleitlager (Querlager) (Externally - Pressurized Air Lubricated Journal Bearings)," VDI - Berichte, Bd 20, 1957, pp. 123-131.

Hydrostatic journal bearings with circumferential supply slots are discussed. When the slot width is too large the shaft does not float unless a restriction is used. A range of restriction sizes is given as a function of film thickness. Laminar flow is assumed and the incompressible fluid equations are used. A Bernoulli pressure drop is assumed to occur between the inlet chamber and the bearing clearance. An expression involving hydraulic radius is used to derive equations for pressure distribution. For analysis purposes the bearing is split into an upper and lower region and the crossflow between regions considered. The results of theory and experiment are found to be in qualitative agreement. The bearing stability characteristics are analyzed and a critical rotation speed determined.

71. BUCK, W. E., "High Speed Turbine - Driven Rotating Mirrors," The Review of Scientific Instruments, Vol. 25, No. 2, Feb. 1954.

A rotating mirror is the basic element in the highest-speed cameras of both the framing and sweeping image types. The factor

of merit of these cameras is determined mainly by the peripheral speed of the mirror. The turbine drive described here will spin the best-quality steel mirror up to its bursting speed. Flat mirrors with faces 17.5 mm wide by 21 mm perpendicular to the rotational axis are operated regularly at 10,000 rps. A camera designed to use these turbines and to take pictures at the rate of 3,500,000 frames per second, with an exposure time of 0.1 sec., is illustrated. (Auth.)

Buck was not able to operate with air-bearings at much over 3,000 rps. However, with liquid lubrication he was able to attain rotational speeds of 13,500 rps. No information is given on the design or development of the air bearings.

72. BUCKLEY, D. H. and R. L. JOHNSON, "Use of Less-Reactive Materials and More Stable Gases to reduce Corrosive Wear when Lubricating with Halogenated Gases,"U. S. NASA Tech. Note D-302, Aug. 1960, 18 p.

Experimental investigation of the effectiveness of sym-dichlorotetrafluoroethane, dichlorodifluoromethane, and sym-dibromotetrafluoroethane as lubricants for metals, ceramics, and cermets. Results show that low-rider wear can be maintained to higher operating temperatures with reactive gas lubrication by using less reactive materials such cermet-metal and ceramic-metal systems as the lubricated components (Aluminum oxide sliding on Stellite Star J was effectively lubricated to 1400 F. by Dichlorotetrafluoroethane). It was also found that sym-dichloro-tetrafluoroethane offers improved chemical internal stability over dichlorodifluoromethane, thereby contributing less to corrosive wear at extreme temperatures.

73. BUCKLEY, D. H. and R. L. JOHNSON, "Halogen'Containing Gases as Lubricants for crystallized-Glass-Ceramic-Metal Combinations at Temperatures to 1500° F., NASA TN D-295, 19 p. Oct. 1960.

Pyroceram 9608 (a crystallized glass ceramic) has been considered for use in high-temperature bearing and seal applications. One of the problems encountered with Pyroceram is the lack of availability of lubricants for the temperature range in which this material becomes practical. Experiments were conducted with Pyroceram sliding on various nickel-and cobalt-base alloys using reactive halogen-containing gases as lubricants. Friction and wear data were obtained as a function of sliding velocity and temperature.

Studies were made with a hemispherical rider (3/16 in. rad., Pyroceram 9608) sliding in a circumferential path on the flat surface of a rotating disk (2-1/2 inch diam. nickel- or cobalt-base alloys). The specimens were run in an atmosphere of the various gases with a load of 1200 grams, a sliding velocity of 3200 feet per minute, and temperatures from 75 to 1500 F.

The gas $CF_2Br$-$CF_2Br$ was found to be an effective lubricant for Pyroceram 9608 sliding on Hastelloy R-235 and Inconel X up to 1400 F. The gas $CF_2Cl$-$CF_2Cl$ provided effective lubrication for Pyroceram sliding on various cobalt-base alloys at 1000 F. (Auth.)

74. BUCKLEY, D. H. and R. L. JOHNSON, "Inhibiting Corrosive Wear in Lubrication with Halogenated Gases at 1500 F by Use of Competitive Reactions and other Methods," Trans. ASLE. Vol. 4, No. 1, April 1961, pp. 33-38.

Various gases were used as corrosion inhibitors for nickel- and cobalt-base alloys in halogen-containing gas lubrication systems. Corrosion experiments were donducted at 1500 F with $CF_2Cl_2$ and various mixtures of gas with inhibitors. One gas found to be a satisfactory inhibitor was air (oxygen). Oxygen reacted at the metal surface in competition with the chlorine of $CF_2Cl_2$, thus reducing corrosion. Friction and wear experiments conducted with a $CF_2Cl_2$-air mixture lubricating $Al_2O_3$ sliding on cobalt base alloy showed low wear and low friction over the temperature range from 75 to 1500 F. (Auth.)

75. BUDD, A. V., "Rotary Engine," U. S. Patent 915 549, issued 1909.

In this invention a pressurized fluid is used to support a vertical load. The same fluid impinging on "buckets" is used to impart rotation to the supported member. The fluid used may be oil, water, steam or other gas.

76. BURGDORFER, A., "The Influence of the Molecular Mean Free Path on the Performance of Hydrodynamic Gas Lubricated Bearings," The Franklin Institute-Laboratories Interim Report I-A2049-2, Contract Nonr 2342(00) Task NR 097-343. Also AECU 3771 from Office of Technical Services. Also Journal of Basic Engineering Trans. ASME Mar. 1959, Vol. 80, Series D, No. 1 pp. 94-100. ASME Paper No. 58-LUB-7.

A modified Reynolds equation is derived for gas-lubricated hydro-dynamic bearings operating under "slip-flow" conditions. Closed analytical solutions are given for a Rayleigh-type step-bearing and an inclined plane slider bearing for the case of two-dimensional flow.

The influence of the molecular mean free path on the performance of bearings of arbitrary form is obtained by means of a small parameter perturbation technique. (Auth.)

The author presents one item of study on the fundamental aspects of bearing lubrication. The work is directly applicable to certain conditions of gas bearing operation including the use of gases such as hydrogen and helium.

77. CAPELLUPO, J. P., A. W. LINDBERG and R. H. MARCUS, "Research on the Feasibility of the Lindberg Gyroscope Principle," Aeronautical Research Laboratories, Wright Patterson Air Force Base, Ohio, Aug. 1960, WADD TR 60-174, 112 p.

A preliminary research study has been conducted to verify the feasibility of a two-rotor gyroscope as a precision, direction-sensing device. The theoretical and experimental work was limited to basic research on two fundamental components of the proposed system.

a/ The direction-sensing device consisting of a two-rotor system using a spherical gas bearing support.

b/ The aerial signal generator, for which an optical type was selected after study of capacity and inductive types.

Research models of each device were constructed from theoretical design considerations and laboratory tests were conducted with these models to establish their operational characteristics under conditions simulating those of the proposed gyroscopes. The refinement of the model using a floating sphere configuration was sufficient to demonstrate operating characteristics such as stability. It also supplied information which, by extrapolation, indicated the feasibility of further improvements. A comparative study was made to show the effect of rotor configuration on gyro performance.

The unique design features of the experimental system were shown to be fundamentally promising. However, more refined experimentation and research models of high precision are required to determine quantitatively the capabilities of this type of gyroscope. (Auth.)

78. CAPRIZ, G., "On Some Dynamical Problems Arising in the Theory of Lubrication," (In Italian.) Riv. Mat. Univ. Parma, Vol. 2, 1960, pp. 1-20.

(Paper not available for review as of July 1, 1961.)

79. CAROTHERS, P. E., "An Experimental Investigation of the Pressure Distribution of Air in Radial Flow in Thin Films Between

Parallel Plates," U. S. Naval Postgraduate School Thesis, 1961, 69 p.

(Paper not available for review as of July 1, 1961.)

80. CARTER, L. F., "Air Supported Gyroscope," U. S. Patent 2 086 896, issued 1937.

The gyroscope described uses spherical shaped air bearings in which the air is caused to flow by lowering the pressure (exhausting) through the opening which is normally used for the inlet.

81. CARTER, L. F., "Air Borne Artificial Horizon," U. S. Patent 2 086 897, issued 1937.

A toroidal (doughnut-shaped) air-lubricated bearing forms part of the air-borne artificial horizon patented. Air flow to exert the torque required to right the gyroscope when necessary is controlled by the motion of a pendulum which is part of the device.

82. CARTER, L. F., "Air Borne Directional Gyroscope," U. S. Patent 2 086 898, issued 1937.

The gyroscope which is the patented item makes use of an air drive and air support. The air is exhausted from between the bearing surfaces rather than being forced in under pressure. The bearings used are shaped in the form of sections of toroids.

83. CARTER, L. F., W. BOLSTER, "Air Borne Gyrocompass," U. S. Patent 2 095 313, issued 1937.

A "heavy" (200 pound) gyrocompass is supported on an externally pressurized gas lubricated, spherical bearing. Pressurized air is also used for damping, and torque restoring purposes. A standby mechanical system of bearings is provided in the event that the air supply should fail.

84. CARTER, L. F., and W. ANSCOTT, "Gyrovertical," U. S. Patent 2 133 809, issued 1938.

In a gyrovertical, a rotor, a rotor bearing casing supporting said rotor and air borne spherical bearing means for supporting

said casing for freedom about all three principal axes. (Official Gazette.)

85. CASTELLI, V. and H. G. ELROD, Jr., "Perturbation Analysis of the Stability of Self-Acting, Gas-Lubricated Journal Bearings," Franklin Inst. Labs. Res. Devel., Tech. Rept. No. I-A2049-11, Feb. 1960, 31 p.; ASTIA No. AD 234 380.

The dynamics of a gas-lubricated journal bearing are studied by using Reynolds' equation and the Lagrangian equations of motion. This system of equations is then linearized by the perturbation method. The stability of the bearing is then investigated by studying the location in the complex plane of the roots of the characteristic determinant of the solution of the system of governing equations. (Author.)

86. CATAANEO, A. G., R. A. COIT, and S. S. SOREM, "Operation of Rolling-Element Bearings in a Protective Atmosphere," Proc. Inst. Mech. Engrs., London, Vol. 174, No. 13, 1960, pp. 479-485.

To operate at high temperatures, up to 1100° F. bearings must be protected against two sources of early failure; formation of red rust by oxygen attack on the surfaces in either rolling or sliding contact, and rapid wear by local seizure (scuffing) of the cage surfaces in sliding contact with other elements. The first function can be filled for all-ferrous bearings by an atmosphere consisting of a mixture of air and an organic vapour which acts as a reducing agent at elevated temperatures. The performance of the second function requires constituents or additives that form anti-scuffing films.

An olefine oxide polymer was found to be a satisfactory reducing agent over the whole temperature range. Conventional extreme pressure (e.p.) additives are effective in preventing scuffing up to about 900° F. Above 900° F. the polymer forms an organic film which itself gives some protection against scuffing. Size 206 tool steel bearings have been operated for 100 hrs. at 1000° F., 10,000 rev/min under considerable radial and axial load; and for 22 hrs. at 1100° F. With the bearings available thus far, maximum loads are dictated by softening of the metals above 900° F.

These high temperatures create special problems in the design of the test equipment with respect to fits, warping and dimensional changes. The rig and procedures used in this work are described.

87. CHARRON, M. E., "Role Lubrifiant de L'Air dans le Frottement des Solides. Frottement dans le Vide (The Role of Air as a

Lubricant in the Friction of Solids. Friction in a Vacuum)," Academie des Science, Session 11, April 1910, pp. 906-908.

The author notes from experiments that the friction between relatively moving surfaces decreases as speed increases until a certain "critical velocity" is reached whereupon the friction becomes constant. This is attributed to the presence of an air layer which acts as a lubricating film. When the same experiment was performed in a vacuum, the coefficient of friction was found to be independent of speed.

88. CHIRONIS, N. "Research Focuses on Gas Bearings," Product Engineering, Nov. 25, 1957, pp. 100-102.

The article gives a summary as of Nov. 1957, of the program of gas bearing research conducted at the Franklin Institute Laboratories under Contract Nonr-2342(00) Task NR 097-343.

89. CHIRONIS, N., "Gas Bearings Take the Stand: Experts Strip Mystery from Gas Bearings," Prod. Engng., Vol. 30, No. 48, Nov. 33, 1959 pp. 68-70.

A review of the First International Symposium on Gas-Lubricated Bearings, Oct. 1959, Current applications in instrumentation and machine tools are emphasized.

90. CHRISTOPHERSON, D. G., "A Review of Hydrodynamic Lubrication," Proc. Inst. Mech. Eng. Conf. on Lube and Wear, London, 1957, "Air Bearings," p. 11.

A brief mention of air lubricated bearings made in reviewing the papers by Ausman and Cole and Kerr presented at the same conference.

91. "Closed-Cycle Gas Supply System" JPL Research Summary No. 36-7, Vol. 1, Dec. 1, 1960, to Feb. 1, 1961, pp. 27-30.

This report describes a test apparatus for a gas-lubricated bearing in a closed cycle pumping system for solar or nuclear energy applications. The apparatus was constructed in order to obtain data for comparison with an analysis set forth in three previous reports, viz., RS 36-1, 36-2, and 36-4. Test results are presented for nitrogen as the lubricant gas as a preliminary to the use of Freon vapor.

92. COLE, J. A., "Gas Lubrication," Research, Vol. 12, No. 8/9, Aug./Sept. 1959, pp. 348-355.

This is a generally informative article in which the author describes the principles and development of gas lubrication, and surveys some current applications. The main headings of this survey deal with film lubrication and its types, the research and development of self-acting gas bearings, and the problem of externally pressurized gas bearings.

The author concludes that while oil will not suffer large scale competition due to these new developments, gas bearings do show promise for many applications, in particular where loads are light, and speeds and temperatures are high.

93. COLE, J. A., and J. KERR, "Observations on the Performance of Air Lubricated Bearings," Paper 95, Hydrodynamic Lubrication, Conference on Lubrication and Wear, London, 1st-3rd Oct. 1957, The Institution of Mechanical Engineers, 1 Birdcage Walk, London, SW 1.

Experiments have been made on self-acting air bearings with clearance ratios in the region of 0.001, running at speeds up to 60,000 rev/min. The results indicate that loads of about 1 $lb/in^2$ (0.07 $kg/cm^2$) per 1000 rev/min can be carried. At low loads, corresponding to calculated eccentricity ratios below 0.2, half-speed whirl occurs. Circumferential pressure distributions have been measured in the bearing mid-plane and show reasonable agreement with available theory . Water condensation has been found to occur under certain conditions in the bearing, but the amount is small and does not seem to affect bearing operation. (Auth.)

The author discusses briefly the advantages and disadvantages of gas-lubrication of hydrodynamically operating bearings, pointing out that, in general, the gas lubricated bearing is more difficult to analyze theoretically. The test bearing bushings were made of glass. An induction motor was used to drive the steel shaft. The main bearings of the test shaft were rubber "o" ring mounted porous bronze, externally pressurized bearings of the type described by Montgomery. With the glass bushes the author was able to visually observe the phenomena occurring within the bearing. Thus he could see moisture condensing in the bearing film and the effect of humidity in the atmosphere. However, because of the poor thermal properties of the glass, temperature distribution within the air film was probably different from that observed. After noting that the temperature differences were relatively small the author states thtt his experiments support the assumption of an isothermal region in the bearing.

The author's film pressure distribution (at the center-line of the bearing) are especially interesting when the positive pressure

region is compared with the theoretical results given by Katto and Soda's solution. (The author uses a factor of 1.5 in his calculations to account for the differences in analysis between finite and infinite width bearings. In comparing the negative pressure regions, however, the author finds experimentally that changes in speed, clearance or load have little effect. The theory of Katto and Soda shows relatively large changes in negative pressure due to changes in load.

In discussing the stability aspects of his bearing the author notes that vibrations were sometimes set up at frequencies of 1/2, 1/4 or 1/6 shaft speed. However, these vibrations died out on increase in speed. In this respect they differed from true whirl (1/2 speed).

94. COLE, J. A., and J. KERR, "Theoretical and Experimental Analysis of Hydrodynamic Gas-Lubricated Journal Bearings," Trans. ASME - J. Basic Engng., Vol. 81, Series D, June 1959, p. 272.

In a letter to the editor, the authors analyze the work, under similar title, by B. Sternlicht and R. C. Elwell (ASME Trans., Vol. 80, May 1958, pp. 865-878). Several points regarding the authors' computational procedure are criticized. It is stated that the boundary conditions are not stated explicitly; that the iteration procedure for $\alpha$ seems unnecessary; that the reference to turbulence is mystifying; and, finally, that additional references might have been usefully included in the author' survey of earlier work on gas lubrication. These references are given by Cole and Kerr in their "letter".

95. COMOLET, R., "Ecoulement D'un Fluide Entre Deux Plans Paralleles Contribution A L'Etude des Butees D;Air (Flow of a Fluid Between Two parallel Plates Contribution to the Study of Air Shock in Bearings)," Publications Scientifiques et Techniques de L'Air No. 334, Sept. 1957, (83 p. 24 fig.) Translated by J. Cherubim and Y. Gagne. Available from Stratos Div of Fairchild with prior approval of author.

The author conducts a systematic study of the two-dimensional flow of a viscous liquid in longitudinal or radial movement between two fixed parallel planes, the law of transformation being of the polytropic type $\frac{P}{\rho^m} = C^{te}$

This study shows a certain generality since it takes into account forces of inertia whose effects are surprising enough when it concerns divergence from radial flow. The formulas obtained permit the deduction of some results already known in the simplest cases.

Experimental testing completes the theoretical study, and it defines the sphere of application of the proposed formulas. For a radially divergent flow, the flow is laminar and isothermal as long as the local Reynolds' number is less than 550.

96. COMOLET, R., "Ecoulement Radial d'un Fluide Compressible Visqueux Entre Deux Plans Parallels (Radial Flow of a Compressible Viscous Fluid between Two Parallel Planes)," Comptes Rendus, Academy of Sciences, Paris, France, Vol. 235, No. 20, Nov. 17, 1952, pp. 1190-1193.

When there is a relatively high pressure drop between the extermally pressurized bearing recess and the bearing edge (ambient), the effects of compressibility are important as is the velocity of flow, the transfer of heat is difficult and the law of transformation tends toward the adiabatic ($n = \gamma$).

97. COMOLET, R., "Etude Experimentale d'un Ecoulement Radial de Fluide Visqueux Entre Deux Plans Paralleles, (Experimental Study of Radial Flow of a Viscous Fluid between Two Parallel Planes)," Comptes Rendus Academy of Sciences, Paris, France, Vol. 235, Dec. 1, 1952, pp. 1366-1369. Translated by A. Talis; Edited by E. B. Sciulli, Franklin Institute Laboratories, Phila., Pa., Sept. 1957.

This is a short article containing experimental verification of a theoretical analysis for the radial flow of a viscous fluid between two parallel plates. The theoretical analysis was developed in a previous paper. The results show that the flow is isothermal, proportional to the cube of the clearance height between the plates and also dependent on the bearing dimensions. The author also shows that the surface roughness of the plates must be considered in determining the clearance height.

98. COMOLET, R., "Radial Flow of a Compressible Viscous Fluid Between Parallel Plates: Theoretical Study and Experimental Research on the Thrust Bearing." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 242-250.

The fundamental problems of flow of a viscous fluid between two fixed parallel plates are two-dimensional $\rho$ For those flows which follow the law of polytropic expansion $\frac{p}{\rho^n}$ = constant, it is possible to integrate the equations of motion and provide a general solution, even including the inertia terms which are usually neglected.

The author describes his particular experiments relating to

radial diverging flow of a compressible viscous fluid in an air thrust bearing. The flow remains laminar if the local Reynolds is smaller than 550.

99. CONSTANTINESCU, V. N., "Asupra Unor Proprietati Si Solutii la Lamita ale Ecuatililor Lubrificatiei cu Gaze (On Certain Properties of the Equations of Gas Lubrication and the Solution for a Limiting Case)," Comunicarile Academiei R.P.R., Mechanica Aplicata, Bucharest, 1955, Tomul V, Nr. 9, (Vol. 5, No. 9), pp. 1317-1321.

In this article the author deals with certain properties of the equations of gas lubrication concerning the values and the locations of the maximum and minimum of the distribution of pressures. These properties are general and apply also for lubrication with oil.

Based on these considerations, one obtains the solution of the problem of gas lubrication in the limiting case, where the relative velocity, V, of the surfaces tends to infinity (7), (11). The solution obtained is general and applies for all polytropic changes of state of the gas lubricant. Its practical application lies in the possibility of using it for calculations of bearings which operate at high but finite velocities, V, because the pressure distribution which results is close to that obtained in the limiting case examined. (Auth.)

100. CONSTANTINESCU, V. M., "Consideratii Asupra Calculului Lagarelor Circulare de Alungire Infinita, Lubrificate cu Gaze (Calculations on the Infinite Length Circular (Journal) Bearing Lubricated with Gas)," Studii si Cercetari de Machanica Aplicata, Acad. R.P.R. Institutul de Mecanica Aplicata, Bucharest, 1955, Vol. 6, No. 3-4, pp. 377-400.

In the first part of this work the author determines, analytically, the pressure distribution for an infinite length circular (journal) bearing lubricated with gas. He then approximates the actual film thickness by two straight lines. He analyzes the nature (effect) of the approximations introduced and the results are compared with those obtained by other authors who have used numerical integration methods. (Auth.)

101. CONSTANTINESCU, V. N., "Consideratii Asupra Calculului Lagarelor Circulare de Alungire Infinite Lubrificate cu Gase (Study of Gas Lubricated Journal Bearings of Infinite Length)," Studii si Cercetari de Mecanica Aplicata, Bucharest, 1956, Vol. 7, No. 1, pp. 81-105.

The characteristics (pressure distribution, friction moment, etc.) of infinite length gas lubricated journal bearings are deter-

mined by use of polar coordinates. The changes in these characteristics as functions of certain parameters is also studied. The results are presented in the form of curves. Suggestions to aid in the use of these curves are also given. (Auth.)

102. CONSTANTINESCU, V. N., "Consideratii Asupra Calculului Lagarelor de Alungire Infinita Lubrificate cu Gaze, Compuse din Suprafete Plane, (Methods for Calculating Characteristics of Infinitely Long Slider Bearings Consisting of Plane Surfaces and Lubricated by Gas)," Studii si Cercetari de Mecanica Aplicata, Bucharest, 1956, Vol. 7, No. 3.

This investigation begins by integration of the differential equation (1) for the situation in which the film thickness delta varies linearly with respect to the distance x in the direction of motion, and also for the case in which this film thickness remains constant. The solutions obtained in the second case are rigorous for isothermal conditions as well as for polytropic expansion of the lubricating gas (kappa not equal to 1). The solutions obtained for the first case are rigorous for the isothermal condition (kappa = 1) and an approximate method is indicated for determining the results for the polytropic case (kappa not equal to 1).

These results are applied to the calculation of certain types of bearings for parallel surfaces (paragraph 2), for surfaces with inclined planes (paragrpah 3), and for the case in which the lubricating film has first order discontinuity (paragraph 4), and a discontinuity of the second order (paragraph 5) and also for other types of bearings (paragraph 6). The pressure distributions, as well as the general characteristics of these bearings are determined. In order to simplify the practical application of these results, they are presented in the form of graphs. The different types of bearings are also studied from the point of view of the maximum load capacity. (Auth.)

The original Rumanian version of this paper contains what would ordinarily be a minor error which, however, has an effect on the results and conclusions. For the convenience of those who do not have a corrected copy available, the error and its corrections are included here.

In equation 98, $(\delta_2/\delta_1)^2$ should have been used instead of its reciprocal. This means that

$$F_1 = F_2 \left(\frac{1-a}{1+a}\right)^2 \frac{l_1}{l_2}$$

The incorrect causes an error in the third equation of 102 from which the constants are determined. (The second part of equation 104 is also incorrect.) When the constants are used in equations 94 and 96, the resulting curves in figures 24 and 25 and No. 3

of figure 26 are not correct.

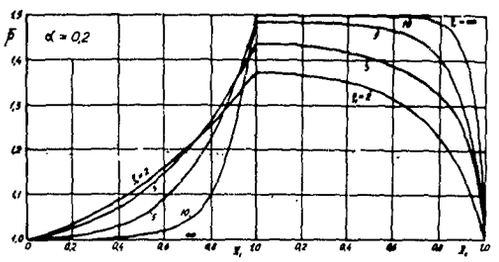

FIGURE 24.

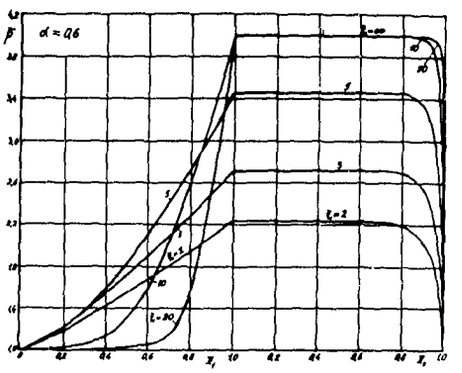

FIGURE 25.

In a letter to FIL dated 12 May 1958 the author submitted the three new figures 24, 25, 26 shown and stated as follows: "I am sending you figures 24, 25 and 26 of my article replotted by taking into consideration the necessary correction to be introduced into relation (98).

The new curves in Figures 24 and 25 seem to show an interesting fact, namely the load carrying capacity (the pressure resultant) would have a maximum value for the value obtained for $_1 = 10$ the corresponding value being a little greater than the value obtained for $_1 =$ (because in the figures, the surface corresponding to the second step remains almost constant, while the surface corresponding to the first step is decreasing).

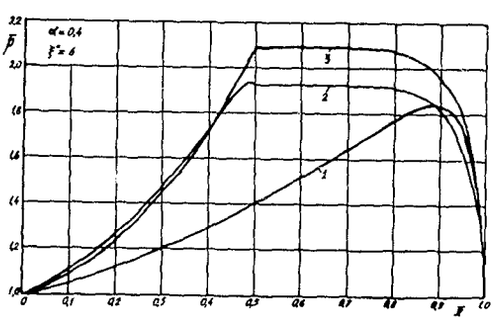

FIGURE 26.

In the Fig. 26 I have now considered * = 6 in order to obtain a greater difference among the curves. The result seems to be an increase of the load carrying capacity for curves 2 and 3, of about two times in comparison to curve 1. At the same time curve 3 gives a load carrying capacity greater than curve 2."

103. CONSTANTINESCU, V. N., "Contributii La Teoria Hidrodinamica A Lubrificatiei Cu Gaze (Contributions to the Hydrodynamic Theory of Gas Lubrication)," Dissertation to obtain title of scientific candidate in technical school: Academia Republicii Populare Romine Institutul de Mecanica Aplicata, Buccuresti, 1955.

The work is composed of four parts: 1) Introduction, 2) Bidimensional problem of gas lubrication, 3) Tridimensional problems of gas lubrication, 4) Final conclusion.

1. Presents the practical importance of the problem and the actual stage of the theoretical and experimental investigations in this direction. Briefly presents the general equations of gas lubrication and the various approximations used in order to simplify calculations.

2. Analyzes the previous forms attained by the differential equation for the case when motion in the lubricant layer is bidimensional. Then, analyzes some properties of this differential equation and finally, the influence of the eventual discontinuities of thickness upon the pressure curves. Chapter II presents some cases of exact integration of the pressure differential equation.

In Chapter III the author studies some limiting solutions of gas lubrication, namely the cases when the relative velocity betwenn surfaces approaches either zero, or infinity. He also studies the case of motionless bearings fed under pressure.

Chapter IV presents an approximate, general method, for solving the bidimensional problem of gas lubrication.

CHapter V presents applications of the above in the calculation of various kinds of bearings.

3. Chapter VI studies the various forms of the differential equation (2.12). Thus, for the case of permanent motion, equation (2.12) is written as (19.2).

Chapter VIII presents an approximate general method of solution for $K = 1$ as well as for $K \neq 1$.

4. Presents some conclusions to the results obtained.

The paper is a summary of the original work performed by the author in order to obtain the title of Candidate. (Degree equivalent to or higher than M.S.).

104. CONSTANTINESCU, V. N. "Contributii la Teoria Lubrificatiei cu Gaze (Contributions to the Theory of Lubrication with Gas)," Travaux de la Session Generale scientifique de la filiale de l'Academie de la R.P.R. de Cluj, 18-21, Dec. 1954.

(Paper not available for review as of July 1, 1959.)

105. CONSTANTINESCU, V. N., "Distributia Presiunilor In Lagarele de Dimensiuni Finite Lubrificate cu Gaze (Pressure Distribu-

tion in Bearings of Finite Dimensions Lubricated with Gas)," Comunicarile Academiei R.P.R. Stiinte Technice, Tomul VI Nr. 5, (Vol. 6, No. 5), 1956, p. 377.

A successive approximation method is presented for solving the differential equation

$$\frac{\partial}{\partial x}\left(\frac{\delta^3}{\mu}\frac{\partial p^{\frac{1}{K}+1}}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\delta^3}{\mu}\frac{\partial p^{\frac{1}{K}+1}}{\partial z}\right)=6V\left(\frac{1}{K}+1\right)\frac{\partial}{\partial x}\left(p^{\frac{1}{K}}\delta\right) \qquad (1)$$

for K = 1. The procedure can be reduced to a single iteration by the introduction of the relation

$$\frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p_\infty^2}{\partial x}\right)=12V\frac{\partial}{\partial x}\left(p_\infty\delta\right) \qquad (6)$$

in the second member of equation (1) above. An analogy can be established between the manner of solving the problems of lubrication with gases and those with oils. This observation permits applying the same methods to calculate (values of) (1). The general solution is given by the expression

$$\phi=\phi_\infty-\phi^*+\alpha z \qquad (9)$$

At the end of the paper is indicated a method of solving equation (1) for $K \neq 1$, the solution of that equation for K = 1 being known. (Auth.)

106. CONSTANTINESCU, V. N., "Lubrificatia Suprafetelor Sferice (Lubrication of Spherical Surfaces)," Comunicarile Academiei R.P.R., Bucharest, 1956, Tomul 4, Nr. 4 (Vol. 4, No. 4).

Spherical coordinates are employed to resolve the equations of lubrication for the motion of spherical surfaces considering the viscosity to be variable. For the usual limiting conditions the solutions are obtained in closed form which facilitates the calculations for pressure distribution and friction moments. A method of solving the problem is also given for the general case. (Auth.)

107. CONSTANTINESCU, V. N., "Repartitia de Presiuni In Lagarele de Alungire Infinite Lubrificate cu Gaze (Pressure Distribution in Infinite Length Slider Bearings Lubricated with Gas)," Comunicarile Acad. R.P.R., Bucharest, Vol. 6, No. 2, 1955, pp. 377-383.

In the case of the infinite length bearing, the general equation (1) is reducible to the first order equation (2) which with the assumption of an isothermal transformation has the appearance of (6). One can find an exact general solution to (6) for plane bearings (fig. 1.), which permits obtaining, after using substitutions (10) and (13), the differential equations with separable variables (16). The appearance of the solutions differ; being given by equations (21), (23), or (24) depending on whether conditions (18), (19) or (20) are satisfied, as functions of the value of the relative velocity between the two surfaces. The region defined by equation (19) is a critical region. The regions defined by equations (21) and (24) are analogous to the subsonic and supersonic regions in the flow of gases.

When considering journal bearings (fig.2) one may use with sufficient accuracy the results obtained for plane bearings; providing that the radial clearance, between the journal and bushing, and the eccentricity of the bearing, e, are small, the variation of lubricant film thickness is very close to two straight lines, AB and BC (fig. 3). (Auth)

108. CONSTANTINESCU, V. N., "Scurgerea Laminara a Gazelor in Straturi Subtire (The Laminar Flow of Gases in Thin Films)". Comunicarile Academiei R.P.R. Bucharest, 1959,Vol. 6., No. 2, pp. 281-284.

In this note, a study is made of laminar flow of a gas between two stationary surfaces when the separation of the surfaces is small relative to the other dimensions. (Auth).

109. CONSTANTINESCU, V. N., "Sur le Probleme Tridimensionnel de la Lubrification Aux Gas (On the Three-Dimensional Problem of Lubrication with Gases)," Revue de Mechanique Applique (Lubrification), Acad. R.P.R., Bucharest, 1956, Tome 1, No. 2 (Vol. 1, No. 2) pp. 123-138. Translated by J. R. Dere and W. A. Gross, IBM Research Laboratory, San Jose, California. Available from John Crerar Library.

The purpose of this study is to present some theoretical considerations on the three dimensional problem of the lubrication with gases.

In the first paragraph, we give the general solutions of the problem for journal bearings at rest under pressure and for both extreme assumptions, $V \rightarrow 0$ and $V \rightarrow \infty$.

In the second paragraph we suggest an approximate general method which may furnish the solution of three dimensional problem of lubrication with gases in the hypothesis of an isothermal evolution of the lubricant gas $\chi = 1$ as well as for $\chi \neq 1$.

These considerations are applied in the third paragraph for the calculation of pressure distribution in circular bearings. (ALth.)

110. CONSTANTINESCU, V. N., "Sur la Theorie des Paliers a Gaz (On the Theory of Gas Bearings)," Revue de Mecanique Appliquee, Vol. 1, No. 1, 1956, pp. 141-155, Academia Republicii Populare Romine Institutul de Mecanica Aplicata, Bucharest, Romania. Translated by W. A. Gross, IBM Corp. Available from John Crerar Library.

A development is given for solving the problem of circular bearings of infinite extent, lubricated by gas, based on approximating the variation of clearance of the lubricant by two straight lines.

The method proposed allows one to obtain analytic expressions for the characteristic quantities of interest in bearings.

The results are compared to calculations and experimental investigations of other authors and good agreement is obtained. (Auth.)

There is currently world wide interest in the theoretical analysis of compressible hydrodynamic film lubrication of bearings. Although more generally useful theoretical developments have appeared in Japan, Great Britain, and the United States, it is well to be aware of developments elsewhere.

Constantinescu has solved an approximation to the isothermal gaseous lubricated journal bearing. He has used exactly the method of Harrison, which the latter published in 1913. Constantinescu has, however, been more thorough in his treatment, and has made comparisons with experimental results recently published in the Soviet Union.

111. CONSTANTINESCU, V. N., "Asupra Stabilitatu Miscaru Lagarelor Circulare Lubrificate cu Gaze." (On the Motion Stability of Gas-Lubricated Journal Bearings) (Russian and French Summaries). Stud. Cercet. Mecan. Aplic. Acad. R.P.R., Vol. 10, No. 1, 1959, pp. 117-140.

The author considers the pressure equation for gas lubrication in the isothermal two-dimensional unsteady case, the time entering in a first approximation as a parameter through the angular velocity of the line of centers. The influence of this rotation on the pressure resultant is manifested through the multiplication of the latter by the factor $1 + \frac{2\Phi}{\Omega_1 + \Omega_2}$ where $\Phi$ is the angular rotation velocity of the line of centers, $\Omega_1$ is the angular rotation velocity of shaft and $\Omega_2$ is the angular rotation velocity

of the bushing. The equations of motion stability are written in compliance with N. Tipei s small perturbation method. A compatibility equation is obtained under the form of a fourth-order equation which is analyzed with the aid of Routh-Hurwitz conditions By giving the magnitude and the direction of the load for the basic undisturbed regime as well as the kinematic and geometric elements of motion, one may calculate their variation with respect to the relative eccentricity and the rotation of the line of centers, and hence the motion stability can be estimated.

Calculations are performed for steady motion and centrifugal loading. On discussing the obtained values, author concludes that, generally, the motion stability of air bearings is not ensured. As distinguished from the case of liquid lubrication, it seems that the eccentricity no longer plays an essential part in the demarcation of the instability zones. The physical explanation of the pronounced instability in the case of gas lubrication lies in the possibility of depression zones being formed due to gas compressibility and expansibility.

112. CONSTANTINESCU, V. N., "Dynamic Stability of Gas Lubricated Bearings". Rev. Mèc. Appliq. Acad. RPR, Vol. 4, No. 4, 1959, pp. 627-642.

This article is based on the author's study published in Stud. Cercet. Mecan. Aplic., Acad. RPR, Vol. 10, No. 1, 1959, pp. 117-140 (See Ref. No.111). It is not a verbatim translation of the Rumanian paper, but the assumptions, theoretical considerations and conclusions are substantially the same.

The author determines criteria for evaluating the stability of gas-lubricated journal bearings and first tries to establish the influence of the dynamical operating conditions on the bearing characteristics, and particularly, the influence of an eventual rotation of the line of centres, (whirl). The author concludes that the motion stability of gas lubricated bearings is not generally ensured at least over a certain speed. The main cause leading to instability is the fact that although the motion is stable in relation to the eccentricity, it is unstable with respect to the angle between the pressure resultant and the line of centers, which he claims is not dependent on the eccentricity ratio , (eccentricity/radial clearance). This conclusion may also be valid for liquid lubricated bearings at very small eccentricities, where the motion may also be unstable. These considerations explain to a large extent the great efficiency of the measures employed in view of ensuring motion stability such as the use of step bearings and the use of pressure supply — both methods leading to a disruption of the equilibrium formerly existing, the former variation of the angle between the pressure resultant and the line of centers being modified. Finally, the author says that in the case of centrifugal load, the phenomenon may be different if the calculation indicates too large depressions or negative pressures which are physically inacceptable. If, however, in the respective ranges, the pressure is set equal to zero the above mentioned results are applicable.

113. CONSTANTINESCU, V. N., "Asupra Comportaru Dinamice a Lagarelor cu Aer "(The Dynamic Behavior of Bearings Lubricated with Air). Stud. Cercet. Mecan. Aplic. Acad. RPR, Vol. 11, No. 4, 1960, pp. 893-908. (Paper not available for review as of July 1, 1961).

114. COREY, T. L., H. H. ROWAND, JR., E. M. KIPP, C. M. TYLER, JR., "Behavior of Air in Hydrostatic Lubrication of Loaded Spherical Bearings," Trans. ASME, Vol. 78, No. 5, July 1956, pp. 893-898.

Some experimental data have been obtained relating the load bearing capacity of air films of various thicknesses and operating at different pressures and rates of flow for 2-, 4-, and 6-in. spherical-type bearings. Semiempirical equations have been developed for calculation of, (a) minimum air pressure as a function of load, (b) minimum flow of air as a function of pressure, and (c) bearing lift as a function of air pressure. (Auth)

Rather complete sets of experimental performance characteristics data are presented in graphical form for externally pressurized spherical thrust-type bearings. One of the parameters affecting the minimum pressure-load relationship is found to be the included angle of the spherical seat. While sufficient information is given to enable one to determine the size sphere and pressures required to support given loads, extrapolation of the data beyond the experimental ranges is not recommended according to the authors.

115. CREWDSON, E., "Improvements in and Relating to Bearings or Journals." Great Britain Patent 548 363, issued 1942.

The use of an externally pressurized gas lubricated bearing is suggested as an inexpensive means for reducing friction.

116. CURRIE, R. B., T. P. ZURFLIEH, "The Design of Equipment for Non-Rotating Testing of Pool-Type Pressurized Gas Bearings," Sc.B. Thesis MIT, Cambridge, Mass., Jan. 14, 1957.

The design of a test apparatus for determining the effects of pool geometry on the load stiffness and stability characteristics of a pool-type pressurized gas bearing is considered. Various subproblems, especially those concerned with generating the pools, varying their size, and dimensional accuracy, are discussed and several possible solutions investigated. A final design is synthesized, incorporating the optimum solutions to the various subproblems. Anticipated performacce of the apparatus for various parameter values is calculated. (Auth)

The design information and other suggestions given may be useful. However, the section entitled "Performance Calculations" does not seem to measure up to the standards previously set. The theory taken from Richardson's work is a bit sketchy and there is insufficient discussion of the curves presented.

117. "Cushion of Air Serves as Thrust Bearing," Compressed Air Magazine, Vol. 59, No. 7, July 1954, p. 205.

Brief article mentioning that an industrial concern employs an air thrust bearing in place of conventional trust bearing.

118. DE FERRANTI, "Air Bearing for High Speeds," Great Britain Patent 930 851, issued 1909.

In textile machinery certain vertical members are subject to high rotative speeds while having little or no radial load applied. The problem here is to separate moving surfaces with as little loss in power as possible. Low viscosity gaseous lubricants are rather ideal for this purpose. However, the inventor effects a substantial increase in the efficiency of the bearing by interposing one or more running bearing parts between the stationary and the highest speed rotating part of the bearing. The weights of all moving parts are supported by air.

119. DE HAVILLAND, "Gas Circulators for Radioactive Circuits," The De Havilland Engine Company Limited, Leavesden Hertfordshire, England.

A four page piece of advertising literature on a commercial device employing gas lubricated bearings.

120. "Detroit's Newest Creation Rides on Air," Providence Journal, April 7, 1958.

A short news item concerning the air supported glide devices made by Ford Motor Company. (See Jay).

121. DEUKER, E. A., H. WOJTECH, "Ecoulement Radial d'un Fluide Visqueux Entre Deux Disques tres Rapproaches. Theorie du Palier a Air (Radial Flow of a Viscous Fluid between Two Disks very Close Together; Theory of the Thrust Bearing with Air as a Lubricant)," Revue Generale de L'Hydraulique, Vol. 17, 1951 pp. 228-238. Translated by L. C. Stephens; Edited by F. A. Raven, Library of Congress, PB112987t.

The paper deals with the flow of viscous fluids between narrowly spaced parallel disks. The momentum term, which is generally neglected, is included in this analysis. By consecutive changes of variables the equations are transformed to an expression which can be integrated graphically. The authors choose instead to make a second series of substitutions which results in equations of the Abelian type which can also be graphed. From the family of resulting curves a solution for the pressure profile in the bearing can be obtained. Both the compressible and incompressible cases are considered in this paper. For the compressible case the author states that, in general one may assume $\frac{p}{\rho^m} = c$ where m varies along the radius. The equations are simplified, however, by assuming that the flow approaches the isentropic at small radial distances from the entry hole and is isothermal over the major portion of the annular region. Conditions at entry of Mach one or less are discussed.

Deuker and Wojtech make a valuable contribution to a subject considered by other authors, (Willis, Welanetz, Paivanas and Robinson). The ambiguous use of certain symbols is rather confusing and this, along with the lack of assumptions or other justification for omitting terms from the original Navier Stokes equations, tends to slow the reader. The derivation is slightly faulty and Comolet calls attention to this as well as to the ambiguity of notation. The experimentally determined curves of pressure profile do not agree as well with either the isentropic or isotheraal curves as they agree with each other. The choice of scale for these curves may lead to the conclusion that the deviation between experimental and theoretical results are not significant.

122. "Development of Hermetically Sealed Centrifugal Pump Unit for Liquid Metals." TID 5143, Library of Congress.

Reference is made to some gas-pressurized bearing tests made on a hydrostatic bearing designed for liquid sodium. Although the load could be supported, considerable vibration was experienced. Attempts were made to eliminate these vibrations but these were abandoned without success.

Only pages 45, 46 and Figures 25, 41, 42, 43, 44 may be directly applicable to the gas-lubricated bearing field.

123. DOWTY, "Gas Bearing Compressors," Dowty Nucleonics Ltd., Brockhampton Park, Andoversford, England.

Advertising literature for commercial nuclear engineering equipment.

124. DRAY, F. "Gas-Lubricated Bearings" BuShips, Vol. 9, No. 11, Nov. 1960, pp. 11-13.

This is a brief review of the principles and applications of gas-lubricated bearings. Sections of this article were abstracted from "General Review of Gas-Lubricated Bearings" presented by Dudley D. Fuller at the First International Symposium on Gas-Lubricated Bearings held in Washington, D. C.

125. DRESCHER, H., "Gleitlager Mit Lufschmierung (Sliding Bearings with Air Lubrication)," V.D.I. Zeit, Vol. 95, No. 35, Dec. 11, 1953, pp. 1182-1190. BuShips Translation 549, also referenced as AEC Translation 3495 availbble Library of Congress or John Crerar Library. Abstract in Engineers Digest, Vol. 15, No. 3, Mar. 1954, pp. 103-107.

This is a very interesting and enlightening paper dealing with the analysis of hydrodynamic journal and thrust bearings operating on air. The author clearly indicates the asset and liabilities of such bearings. Such bearings are desirable for high temperature work as temperature has little effect on the viscosity of a gas. They are helpful where contamination from ordinary lubricants must be avoided. Their use also results in exceedingly low friction even at high sppeds. These bearings are of course limited in load-carrying capacity and a reasonable maximum value is about 5 psi. Clearances are necessarily small so that dust and dirt contamination must be prevented to avoid seizure. Also hydrodynamic whirl is a matter of consideration because air bearings frequently develop this condtion as do lightly loaded oil lubricated bearings. The author discusses these various aspects of air bearing performance and presents experimental data on friction, load-carrying capacity of stable bearing designs, and eccentricity locus for a plain journal bearing and for a recessed stable design of bearing. He describes several applications to electric motors that have proved to be very reliable and satisfactory.

126. DRESCHER, H., "Special Features of Self-Acting Air Bearings and Their Effect on Practical Application." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C. Oct. 26-28, 1959. pp. 319-345.

This report deals mainly with limits imposed on the applicability of gas-lubricated bearings. At low speeds the hydrodynamically induced load-carrying capacity is insufficient and wear takes place, whereas at high speeds a troublesome kind of instability may develop. Experimentally determined characteristics of gas-lubricated bearings under mixed friction conditions are discussed from the point of view of bearing design. Stable operation can be achieved at high speeds by selecting a suitable bearing geometry. Under extreme condtions, hydrostatic bearings are preferable.

127. "Driven Races Reduce Bearing Friction", Power Transm. Design, May 1559, pp. 62-63.

A brief article quoting the "frictionless" gyro and the guidance system developed by Sperry Gyroscope Co., Div. of Sperry RandCorp., Great Neck, N. Y.

128. EDELSTEIN, M. I., "The Characteristics of a Hemispherical Air Bearing at High Rotational Speeds." Curtiss-Wright Corp. Report No. R-48-19, October 19, 1948, AF W33-038ac-14161, Project MX 772. ASTIA - ATl 159 532.

The characteristics are discussed of a sphere rotating at high angular velocities in a hemispherical air bearing. It is used as a position gyroscope.

Theoretical values of friction are reconciled with experimental data. The author uses a modification of a theory developed by Wagner (Wagner, C., "Air Friction in Gaps of Gyro," Tech. Report GS-ORD No. 35, Ft. Bliss, Texas.) to find the friction in the bearing and claims excellent agreement between theory and experiment, providing an additional factor amounting to 33% of the calculated friction is included. This is by no means as arbitrary as it sounds since frictional torques of less than one gm-cm are being considered. In all, some six gas-inlet designs were investigated. With one of these (center-hole), vibration was encountered at 4800 rpm. Stability was achieved by use of additional inlet holes. When using hydrogen as the fluid, the vibration phenomenon was encountered at 12000 rpm even when the design included other inlet openings in addition to the center hole.

The experimenters were not able to attain the desired high rotational speeds with an electric motor drive. Although they finally used the equivalent of an air turbine to spin the rotor at a faster rate, the data for these runs are not included.

The experimental work presented seems to be rather thorough but for the low speeds only. Extensions of this work are contained in other reports prepared at Curtiss-Wright Corp.

129. EDELSTEIN, M., A. KRAUSZ, T. WEDGE, D. FOLEY, D. MAXWELL, W. HORTON, "The Development of a Gas Supported Rotating Sphere for Use as a Stable Element," Curtiss Wright Corp., Element Report No. R-49-22. Also ASTIA ATI 65-474.

It was originally proposed to investigate the feasibility of utilizing a gas bearing to support a spherical gyroscope rotor. Based on the conlusions of this investigation a low drift gyroscope was to be designed, constructed and tested.

This report contains a discussion of the theoretical background, design criteria, and the favorable experimental data of a novel two-stage gyroscope for use as a stable reference for guided missiles or conventional aircraft. (Auth).

This is a rather complete report with about half of it devoted to the air bearing. The bearing analysis assumes the fluid to be incompressible and makes use of a power series to effect a solution for, div ( $\mathcal{E}^3$ grad P) = 0, the fundamental differential equation for the flow. This method follows that employed by Dr. Lummig of MIT and is somewhat similar to the perturbation method Ausman used a few years later. However, the equations in this report are a bit more complicated since the authors of this paper were dealing with a sphere.

130. EGLI, A., "The Leakage of Gases through Narrow Channels," Journal of Applied Mechanics, Trans. ASME, Vol. 4, No. 2, June 1937, pp. A 63-A 67.

In this paper a rational theory is developed as a basis for calculating the flow of gases (compressible fluids) through narrow channels. For the most important case the solution of the general flow equation is given in graphical form which shows the relation between mass flow, pressure drop, and channel resistance.

Tests of the leakage of air and steam through the narrow clearance between a valve stem and bushing afford a practical demonstration of the use of the theory. Formulas are derived for the calculation of the leakage of gases through reamed bushings on ground stems. Expressions for the leakage of liquids (incompressible fluids) are obtained as special cases of the gas formulas. (Auth)

The author's contribution on the leakage in labyrinth-type seals may also prove applicable to end-leakage in gas-lubricated jounal bearings, especaally those which are externally pressurized.

131. "VIII. Electronic Circuit Elements. A. Gas Bearing Tests. B. Load Carrying Capacity of Gas Bearings" JPL Combined Bimonthly Summary No. 66. Oct. 6, 1958, pp. 58-63.

This report compares theory and experiment for the gap height $h_0$, the gas flow rate $\underline{Q}$ of a circular thrust bearing (derived from Euler's equation) and the load $\underline{F}$. A method was developed to electrically determine $h_0$ from the capacity of the pad cavity. A capacitance bridge served to measure the capacity between load plate and orifice plate.

The flow rate $\underline{Q}$ was measured by means of a variable-area type of orifice meter in the intake line to the plenum chamber.

Bearing loads were determined by measuring the pressure in the air chamber above the piston with a pressure gage which was calibrated in pounds by means of a strain-gage type of dynamometer

interposed between the piston and the support table.

It is concluded that the theoretical expressions for $h_o$, $\underline{Q}$ and $\underline{F}$ describe the performance of hydrostatic pad bearings and step bearings very accurately.

132. ELROD, H. G., "A Derivation of the Basis Equation for Gas-Lubricated Slider Bearings," Tech. Memo Jan. 11, 1958, Friction and Lubrication, Franklin Institute Laboratories, Philadelphia.

The purpose of this memorandum is to derive the differential equations describing the fluid-dynamical phenomena in a gas-lubricated slider bearing. Only a preliminary attack is made on the general problem of gas lubrication, but the development presented indicates that the small parameter technique employed for fluids having constant properties, can also be readily used for gases as well. To retain simplicity in this preliminary work, side leakage in the bearing is neglected, and the specific heats, thermal conductivity and viscosity of the gas are treated as constant. (Auth)

An analytical derivation is given. The author arrives at the equation for pressure similar to that used by Harrison. It is a bit more general than Harrison's expression in that the heating effect can be included by use of a small parameter. However, the actual integration is not shown; the author merely stating that a more complicated differential equation for pressure would result.

133. ELROD, H. G., "A Derivation of the Basic Equations for Hydrodynamic Lubrication with a Fluid Having Constant Properties," The Franklin Institute Laboratories Interim Report I-Aa209-5, April 1959, Contract Nonr-2342(00), Task NR 097-343. ASTIA No. AD-215687.

In this report small parameter techniques are used to derive Reynolds' lubrication equations, and refinements thereof, from the full Navier-Stokes equation, for fluids having constant properties. An effort has been made to retain vigor in the development comparable to that used in present-day boundary-layer developments. Analytical techniques similar to those employed here have been adapted to the derivation of equations applicable to fluids having pressure and temperature-dependent properties, such as gases. The results will be presented in a subsequent report.

To derive the differential equations for flow in a curved film or arbitrary thickness requires the use of general tensor analysis. The mathematical manipulations are somewhat involved, but one of the results -- a refind Reynolds' equation --can be simply written for a journal or slipper bearing as follows:

$$\frac{\partial}{\partial x}\left\{h^3\left(1-\frac{h}{D}\right)\frac{\partial p}{\partial x}\right\}+\frac{\partial}{\partial z}\left\{h^3\left(1+\frac{h}{D}\right)\frac{\partial p}{\partial x}\right\}=6\mu U\frac{\partial}{\partial x}\left\{h\left(1-\frac{h}{3D}\right)\right\}$$

Here: D = shaft diameter (infinite for a slipper bearing)
h = film thickness
p = fluid pressure
U = shaft surface velocity
x = distance around shaft in direction of rotation
z = distance parallel to shaft axis
$\mu$ = fluid viscosity

The error of the above differential equation is of the order of $(h/L)^2$, where L is the film length in the direction x. In all but the most unusual of applications, both h/L and h/D are exceedingly small for real bearings. Thus, the present analysis justifies the applicability of Reynolds' equation for the constant property fluid. (Auth)

134. ELROD, G., Jr. "The Theory of Pulsating Flow in Conical Nozzles" Franklin Institute Labs. Res. Devel., Tech. Rept. No. I-A2049-15, Feb. 1961, 20 p.

A knowledge of the dynamic characteristics of nozzles and orifices is important in many control and stability analyses of engineering devices. It is usual to assume that the instantaneous flowrate, for a given set of inlet conditions and outlet pressure, is the same as the non-transient value for the same operating conditions. Recently, in connection with the stability analysis of an externally-pressurized thrust bearing, the validity of this assumption was questioned. The analysis presented in this report was undertaken to provide an answer.

The present analysis applies to any fluid, liquid or gas, flowing into a simple conical nozzle. The amplitude and phase of the mass-flux response to a sinusoidally time-variable pressure fluctuation at the nozzle exit are determined. An approximate formula is given for these quantities in terms of the nozzle throat area, the solid angle subtended by the cone, the velocity of the fluid at the nozzle throat, the acoustic velocity at the throat, and the frequency of the pressure fluctuation. (Auth)

135. ELROD, H. G. Jr. and A. BURGDORFER "Refinements of the Theory of the Infinitely-Long, Self-Acting, Gas-Lubricated Journal Bearing." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., October 26-28, 1959, pp. 93-118. (Also Franklin Inst. Interim Rept. No. I-A2049-10, Jan. 1960; OTS No. AECU - 4688; ASTIA No. AD-232 705)

The lubrication equations for an arbitrary Newtionian fluid are derived directly from the general equations for conservation of mass, momentum, and energy. From the lubrication equations an inequality is obtained for the internal film temperture rise.

The isothermal film equations are then derived. Then, for perfectly-aligned self-acting journal bearings, a conservation equation is obtained. For gas bearings this conditions gives: $\int p^2 h^3 d\theta =$ constant along the axis of the bearing. Application of this condition to the infinitely-long gas bearing gives more accurate pressure solutions for this case.

The Katto-Soda form of the differential equation for the infinitely-long bearing is solved by a series expansion in the eccentricity ratio, the first terms of which give the original, approximate Katto-Soda solution. In addition, solutions obtained numerically by digital computations are presented in graphical and tabular form for eccentricity ratios from 0-0.9 and compressibility bearing parameter $\Lambda$, from 1 to $\infty$

Design charts based on these calculations are provided.

136. ELROD, H. G. and S. B. MALANOSKI "Theory and Design Data for Continuous-Film Self-Acting Journal Bearings of Finite Length"

Franklin Inst. Labs. Res. Devel., Tech. Rept. No. I-A20;9-13, Nov. 1960, 51 p.

The general theory of continuous-film lubrication is presented. The results of gas-lubricated bearings are shown to be capable of generalization to any fluid with a linear-pressure-density relation. In particular, the results are applicable to lightly-loaded bearings employing any single-phase substance.

Gas-bearing design formulas for both infinite and finite-length bearings are summarized in the cases of $\Lambda \to 0$, $\varepsilon \to 0$, $\Lambda^{-1} \to 0$.

A new analysis for edge-effects in finite gas-bearings operating at high speed is presented. Finally, rapid slide-rule methods are illustrated for constructed load coefficient and attitude angle curves. (Author)

137. ELWELL, R. C., R. J. HOOKER and B. STERNLICHT "Gas-Bearing Stability Study - Vertical Rotor Investigation" General Electric Co., General Engng. Lab., Contract No. NONR - 2844(00), Task NR 097-348; ASTIA No. AD237 432; May 1960, p. 64.

An analytical and experimental study of the stability of vertical rotors, supported by self-acting gas bearings, is reported. Three main groups of results are presented.

1. Forced vibration of an unbalanced rotor.
2. Unstable rotors with flexible drive.
3. Instabilities of a direct drive (integral electric motor).

Methods of calculating forced vibration amplitudes due to unbalance, are presented, based on previous analytical work, and supported by experiments reported herein.

The unstable behavior of a variety of rotors is presented, to illustrate a commonness of half-frequency conical whirl, and its persistence.

Methods of calculating the "threshold of half-frequency whirl" are given, and verified by experimental results obtained onn three different rotors. The technique predicts the mode of whirl to be encountered, and is a useful design tool. (Author)

138. ELWELL, R. "Observations on the Performance of Self-Acting Gas Journal Bearings" General Electric, Schenectady, N. Y., ONR Contract. No. NONR 2844(00) March 3, 1961; ASTIA No. AD 253-820; 31 p.

This report presents the results of investigations into two different aspects of the performance of self-acting, gas-lubricated bearings. Although the subjects are not directly related, the observations in each case are the result of various experimental investigations. As such, they illustrate the use of experimental results in the construction of more general theories.

The first part of this report discusses a new theory for the occurrence of the phenomenon of half frequency whirl in plain journal bearings. This instability is one of the most serious problems in the application of these bearings today. An evaluation of the stability of these bearings is presented on the basis of different forms of energy contained within the gas film. The objective of this analysis is to furnish a simple, easy-to-use, method of predicting the threshold of this destructive instability. Means can then be provided for raising this inception speed above the operating range of the equipment. As such, it is subject to simplifying assumptions which limit its accuracy of Calculation in some circumstances. Nevertheless, in the comparisons which are carried out with the scant data available, the results are consistent with most experimental observations.

Part II of the report dpesents the results of an experimental investigation of moisture condensation in the gas film of bearings under a rotating unbalance load (synchronous whirl). Wide variations in relative humidity, L/D ratio, load, and speed, were employed. The results, though coarse, show a consistent effect due to the ratio of bearing load to ambient pressure.(Auth).

139. EUSEPI, M. W. and D. D. FULLER "Progress Report on the Development of Gas Bearings for Two Closed-Cycle Gas Turbine Rotors" From "Gas Cooled Reactors" a Symposium Sponsored jointly by the Franklin Institute and the American Nuclear Society, Del. Valley Sect., Monograph No. 7, May 1960, pp. 326-347.

A progress report showing development of gas bearings for two closed-cycle gas-turbine rotors is presented. Design and experimental data are given showing the advantages and disadvantages of this type of bearing application.

Several types of bearings for the early rotor were investigated with the final choice being a seven-pad, self-compensating Kingsbury-type thrust bearing with tilting-pad type crowned shoes, and two tilting-pad type journal bearings were externally pressurized, the upper pad self-acting. Rotational speeds as high as 20,000 rpm were obtained. Final development of the thrust bearing was halted due to termination of the project.

The journal bearings and the thrust bearing for the present rotor are externally pressurized without tilting pads. However, each bearing surface is divided into three equal segments by appropriate grooving. Full loads have been successfully carried by the bearings during non-rotational tests. Full speed, full load tests have not been completed to date. (Author)

140. EUSEPI, M. W. and D. D. FULLER "Interim Report on the Development of Gas-Lubricated Bearings for Closed-Cycle Gas-Turbine Rotors" Franklin Inst. Labs. Res. Devel. Tech. Rept. I-A2049-14, June 1961, 48 p.

A progress report showing development of gas bearings for a closed-cycle gas-turbine rotor is presented. Design and experimental data are given showing the problems involved in the application of these bearings.

The journal bearings and the thrust bearing for the rotor described in this report are externally-pressurized without tilting pads. Each bearing surface is divided into three equal segments by appropriate grooving. Full loads have been successfully carried by the bearings under non-rotational tests. Full-speed, full-load tests have not been completed to date. (Author)

150 FERRAND, W. A., "An Air-Floating Disk Magnetic Memory Unit," Datamation, Nov. - Dec. 1957 pp. 38-41.

Mention is made of an air lubricated hydrodynamic thrust type bearing and its application to a computer component. The sketches and description given are adequate for this article. However, there is probably insufficient theory or design data presented to be of great value to persons working in the bearing field.

142. FIRTH, D., "Electric Dynamometer of High Precision Air Lubricated Trunnion Bearings Employed," Engineering, Vol. 179, May 20, 1955, pp. 628-630.

A high precision swinging-frame electric dynamometer has been developed for measusing the efficiency of hydraulic machinery. It is accurate to within ± 0.1 per cent of full scale torque and is reasonably portable. Novel features include pneumatic trunnion bearings, hydraulic torque measurement, and electronic speed control to within 0.1 per cent over a wide range. The development of the design is described and design features for larger dynamometers are suggested. (Auth)

143. FISCHER, G. K., J. L. CHERUBIM and D. D. FULLER, "Some instabilities and Operating Characteristics of High Speed Gas Lubricated Journal Bearings," ASME Paper 58-A-231.

Various factors influencing the stable operation of high speed rotors on gas lubricated journal bearings have been isolated such as; critical speed, unbalance, film stiffness, whirl, damping and air hammer. Experimental data are given for a number of bearings to illustrate the effects of these factors on operation of gas lubricated bearings and correlation to mathematical analysis. The isolation and understanding of these factors have been due primarily to the instrumentation developed. Rotor assemblies on 1/2" and 3/4" diameter shafts have been successfully run on hydrostatic and hydrodynamic air bearings at speeds up to 165,000 rpm. (Auth)

144. FISCHER, G. K., J. L. CHERUBIM and O. DECKER, "Some Static and Dynamic Characteristics of High-Speed Shaft Systems Operating with Gas-Lubricated Bearings." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct.226-28, 1959, pp. 383-417.

A number of factors have been isolated that influence the stable operation of high-speed rotors running on gas-lubricated bearings. These are "critical" speeds, unbalance, film stiffness, whirl and air hammer. Experimental data are given for a number of bearings to illustrate the effects of these factors and their correlation to mathematical analysis. The isolation and identification of these factors have been due primarily to inssrumentation developed. Rotor assemblies of 1/2 inch and 3/4 inch diameter shafts have been run successfully on externally-pressurized and self-acting air bearings at speeds up to 165,000 rpm. Further insight into externally-pressurized action has been gained through the determination of flow patterns for several types of thrust and journal bearings. An application to a turbo-expander is described where a 7 pound rotor operated at speeds up to 55,000 rpm and was supported by 1-1/4 inch-diameter gas bearings.

145. FORD, G. W. K., D. M. HARRIS, D. PANTALL, "Principles and Applications of Hydrodynamic-Type Gas Bearings," A.E.R.E. ED/R 1662, Revised Version of A.E.R.E.E/R 1140, Harwell Berks, Sept. 1955. Proceedings of the Institution of Mechanical Engineers, Vol. 171, No. 2, 1957, pp. 93-113. Discussion pp. 113-128, "Gas-Lubricated Bearing." Machinery Market, Nos. 2923, 2924, Nov. 23, 1956, pp. 27-30; Nov. 30, 1956, pp. 26, 28 and 30.

The first reference contains the original data and curves and is more complete than the second reference. The third reference is little more than an abstract.

In this paper are described an experimental investigation of properties and some developments in the utilization of hydrodynamic-type gas-lubricated bearings, of both journal and thrust types, as distinct from hydrostatic bearings. Two specific developments are described, the one a pump for circulating carbon dioxide gas at 100 lb. per sq. in. gauge and 150 deg. C. through a loop in a nuclear reactor, the other a gas-bearing motor driving a pump for molten radioactive bismuth, the whole within a hermetically-sealed container. The simple machining requirements and special design principles are described. The performance of gas bearings may be predicted from normal liquid bearing theory if the loading is so small that the pressure rise within the bearing is a small fraction (for example, 10 per cent) of the ambient pressure. For higher pressure ratios compressibility effects must be taken into account. The experimental results and techniques used are reported, those for plain journal bearings embracing a wide range of working conditions and absolute size including compressible flow operation. An explanation of the physical reasons for the change in performance in compressible flow bearings is given. The dynamic instability sometimes encountered in journal bearings and methods of avoiding it are also discussed. (Auth)

This is a somewhat critical review of hydrodynamic gas-lubricated bearings which includes a discussion of the differences between gas and liquid lubrication from both the theoretical and practical viewpoints. On the subject of hydrodynamic gas bearings the paper contains much enlightening information, for example, the relatively high loads that can be carried, the "large" permissible clearances, and the class of surface finishes that can be employed.

The authors, in this paper, present various curves of theoretical and experimental results for journal bearings. They also show some photos and sketches of test equipment. Their discussions also include short sections on half-speed whirl, several types of thrust bearings and applications of gas bearings.

146. FORTESCUE, P., "The Derivation of a Generalized Chart for Viscosity Plate Performance," Atomic Energy Research Establishment, ED/M 21, 1955.

(Paper not available for review (classified) as of July 1, 1959.)

147. FOX, G. R. and H. J. SNECK "Orifice Flows in Externally-Pressurized Gas Bearings." First Intern. Simp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 482-496..

The analysis and design of an externally-pressurized, orifice-compensated, gas-lubricated bearing requires that the feeding device and bearing proper be considered as a unit. Considered individually, each of the components is relatively complex; but when the two components must be treated as a system, the problem becomes extremely complicated. This situation calls for a simple means of predicting the performance of the feeding device consistent with experimental verification.

In the analysis presented, both comprehensive and simplified methods are proposed and evaluated by comparison with experiment. Keeping in mind this objective, it is not intended that the results presented shall be in any way definitive, but that they fill the purpose stated above. For this reason, such refinements as variations of discharge coefficient with Reynolds' number and orifice size, effects of special orifice aperture shapes, etc., were considered contrary to the stated objective.

The effect of the feeding device on bearing performance is discussed. In many gas bearing applications, maximum stiffness is desired. An approach is outlined for designing the feeding device to meet these requirements.

148. FRANKEL, S. R., "An Analysis of a Simple Hydrostatic Gas Bearing Including Compressibility Effects," M.S. Thesis, Mechanical Engineering, Drexel Institute of Technology, Phila., Pa., June 1958.

The use of a gas as a lubricant in bearings has increased in the past few years because of the need to supply a reliable lubricant under a wide range of ambient conditions. This paper is restricted to an investigation of a simple, nonrotating, hydrostatic gas thrust bearing in which air acts as the lubricant. In this analysis the compressibility effects are included among other design parameters, such as film thickness, load carrying capacity, and supply pressure, for subsonic flow conditions. (Auth)

The author, using a series solution, derives an equation for the load carrying capacity of an externally pressurized cirular thrust bearing. The customary assumptions of isothermal flow in the bearing gap and isentropic flow through the entrance restriction are made. Differences between experimental and theoretical load carrying capacities exemplified by their respective pressure profiles as shown on graphs included by the author, are laid primarily to the lack of stiffness of the bearing plates and the inability to fully account for the flow condition at the restriction.

149. FRANKLIN INSTITUTE, "FIL to Build Gas Lubrication Science," Laboratory Report, Vol. 5, No. 2-3, Dec. 1956 - Mar. 1957, p. 5. The Institute News, f Vol. 22, Mar. 1958, p. 3. Journal Franklin Institute, Vol. 265, Mar. 1958, pp. 243-244. Laboratory Report, Vol. 3, Sept. 1554, p. 3.

Contains various items of news and general information about a program of gas bearing research jointly sponsored by eleven departments of the U. S. Government which come under AEC, Dept. of Defense, Maritime Adm. and NASA. The program is administered by ONR.

150. FREDRICKSON, J., "Bearing for Car-Axle," U. S. Patent 1 067 727, issued 1913.

The inventor proposes air supported pistons to carry the load on railroad journal bearings. For this purpose the familiar partial bearing is replaced by a large block with an opening in it for the journal. Pressurized air, under the engineer's control, enters a chamber formed by the journal, the bearing block, and a vertical piston located in the block, and perpendicular to the journal. As the piston is raised the weight on the arch bar is raised with it. Actual lubrication is accomplished by a lubricating material (not specified) in contact with the lower surface of the journal.

151. FROST, A. "Improvements in and Relating to Gas Bearings" Great Britain Pat. 869,200. May 31, 1961, 6 p.

This invention relates to gas bearings of the hydrodynamic or self-acting type. The special feature is that the shaft is stationary and the bearing sleeve rotates (wagon wheel Bearing). The clearance is maintained at a small value. Thrust bearings with gimbal aligning devices are also shown. Details are provided on applications to a self-contained, motor-driven centrifugal compressor and to a textile spinning spindle.

152. FULLER, D. D., "A Survey of Journal Bearing Literature," ASLE, Chicago, 1958. Published by American Society of Lubrication Engineers, 1958 "Gas Lubricated Bearings," pp. 87-89.

The author, in reviewing journal bearing literature, discusses gas lubricated bearings. Most applicable references up to Dec. 31, 1954 are included in this bibliography.

153. FULLER, D. D., "Air Bearings-Low Friction," Lubrication Engineering Vol. 9, No. 6, Dec. 1953, pp. 298-301.

In this paper, the author, speaking of the possible and probable applications of air bearings, describes a few designs including a step bearing for an ultra-centrifuge.

This work by Fuller is a revision of the paper, "Low Friction Properties of Air-Lubricated Bearings." However, it also includes an additional numerical example. This material is also found in his text book.

154. FULLER, D. D., "Air Lubricated Bearings," Mach. Des., Apr. 1953, pp. 272, 273, 381, 384, 386.

Brief article containing same information presented in author's paper, "Low Friction Properties of Air Lubricated Bearings."

155. FULLER, D. D., "Annual Report ONR Project A2049, "The Franklin Institute Labs Interim Report I-A2049-3, July 15, 1958, Contract Nonr-2342(00), Task NR 097-343, AECU 3773, OTS. ASTIA No. AD-200978

This is a summary report on the activities of the research program conducted under Contract Nonr-2342(00), "Research on Gas Lubricated Bearings," for the first year of effort April 1, 1957 to April 1, 1958.

156. FULLER, D. D., "Low Friction Properties of Air-Lubricated Bearings," Trans. N.Y. Academy of Sciences, Series II, Vol. 15, No. 4, Feb. 1953, pp. 9a3 .

The author speaks of the benefits of air bearings and starting from the relationship $F = \mu A \frac{dv}{dy}$ shows, mathematically, the low friction losses for such a bearing. Quoting Brubach, low cost air bearings made from hypodermic syringes are described. Also described is the model of the famous air-lubricated Kingsbury thrust bearing.

Appropriate equations are given for hydrostatic step bearings and drawings are shown of this and other types of air-lubricated bearings including one used in an ultra-centriguge. Noting that the compressibility of the gas must be considered for high loads, the author derives applicable relations for the step-bearing starting from Euler's equation for steady, one dimensional flow with friction.

157. FULLER, D. D., "Theory and Practice of Lubrication for Engineers," John Wiley & Sons, Inc., 1956, pp. 287-305.

The author includes a brief history of air bearings and mentions their advantages and disadvantages. Numerical examples are used for designing self-acting and externally pressurized bearings. At the time this was written, no other textbook contained as much information on gas bearings.

158. FULLER, D. D., "General Review of Gas-Bearing Technology." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 1-29.

This paper reviews some of the general aspects of the subject of gas-lubricated bearings. The special characteristics of these bearings that make them of particular interest are described. These unique characteristics encourage applications of extremes of speed and temperature, permit operation with very low friction and avoid contamination problems that could result from the use of bearings with conventional lubricants. Present and anticipated areas of application are listed. Simple design parameters are described and illustrated with special interest centered around the various forms of the compressibility bearing parameter $\Lambda$ for hydrodynamic or self-acting bearings and the load coefficient $C_L$ for hydrostatic or externally-pressurized bearings.

The difficulties associated with the compressibility characteristics of the gas film as well as its low damping properties are outlined in considerable detail. Steps are shown for both the prediction and control of these difficulties.

159. FULLER, D. D., "Where Is Science Taking Us?" Saturday Review, April 2, 1960, p. 52.

This is an article for the layman. In a condensed and easily digestable form, the author describes the use and advantages of gaseous lubricants in our space-age. The stringent demands concerning friction, leakage or seepage, and a temperature range from - 400° F to perhaps + 2,000° - 3,000° F cannot be met by other lubrication systems except the gas-lubricated bearing. The author emphasizes that gas lubricants are not limited to small, instrument-type bearings. Conversely, large bearings capable of carrying heavy loads (up to 4,000 pound load) have been built. Special emphasis is given by the author to the stability of gases over a wide range of operating conditions, and also to the unlimited variety of gases (even highly corrosive if need be) employed in lubrication.

160. "Gas Bearing for High Pressure Helium Turbine," NP 3683, Classified, AEC.

The only information available comes from "The Reactor Handbook, Volume 2 Engineering" published by McGraw Hill. Page 472 shows a drawing of this bearing and on page 475 is noted the following:

A gas bearing (as well as a combination thrust and journal bearing) is shown in Fig. 3.6.11. The journal bearing consists of four pockets, as shown in section "AA", to which high-pressure gas is admitted through individual orifices, and from which the gas is discharged through the annular clearance space between the sides of the pockets and the shaft. Since the leakage area from each pocket depends upon shaft position, any transverse shift of the shaft will alter the gas pressure in the pocket and provide a restoring force to recenter the shaft. The thrust bearing operates on the same principle, except that the annular pockets are continuous and the gas is discharged through the clearance areas at the inner and outer diameters of the bearing.

161. "Gas Bearings for High Temperatures." Performance Pediction for 1200F Operation" Electromechanical Design, Vol. 3, No. 12, Dec. 1959, pp 32-35.

It is reported that Analogue Controls Inc. of Hicksville, N.Y., developed the design capability to predict performance of several types of bearings with reasonable accuracy prior to their operation. A preliminary design of a bearing is presented for what might be a typical set of requirements. (1) The working fluid or lubricant is air at 1200F. (2) External load at start-up is only rotor weight and load is applied as a direct function of speed until a maximum total load of 50 lbs. is on the bearing. (3) No thrust loads are present. (4) The rotor weighs 2.5 lbs. (5) The maximum speed at 50 lbs. load is about 100,000 rpm. (6) Ambient pressure is atmospheric pressure at sea level. (7) Load is undirectional.

162. "Gas Bearings, JPL CBS No. 63," Combined Bimonthly Summary No. 63,, Jet Propulsion Laboratory, Cal. Tech., Pasadena, Calif., ORDCIT Project, Contract No. DA-040495, ORD. 18, Dept/ Army, Ord. Corps.

This is a resume of the work being conducted on hydrostatic gas bearings at Jet Propulsion Laboratory. It includes mention of their analytical and experimental studies and a brief discussion of their test rig. The entire resume takes less than two pages and, therefore, one should not expect to find any detailed account of the work done.

(See other reports from same source.)

163. "Gas Bearings, JPL CBS No. 66," Combined Bimonthly Summary No. 66, Jet Propulsion Lab., Cal. Tech., Pasadena, Calif. ORDCIT Project, Contract No. DA-04-495-ORD 18, Dept. Army, Ord. Corps.

A thorough study of the existing literature and patents on hydrostatic bearings is now in progress. The purpose of this search is to establish the state of the art and to explore areas for fruitful research and development efforts. The design of gas bearings for specific applications would be greatly facilitated by a comprehensive theory which would permit the prediction of the behavior of such bearings under varying load and environmental conditions. (Auth)

164. "Gas Bearings JPL Summary No. CBS 67," Combined Bimonthly Summary No. 67, Jet Propulsion Lab., Calif. Inst. of Tech., Pasadena, Calif., Oct. 15, 1958, ORDCIT Project Contract No. DA-04-495, ORD 18, Dept. Army, Ord. Corps.

Externally pressurized, multi-orifice, gas lubricated, semi-cylindrical journal bearings were studied as part of a long range program on gas bearings.

165. "Gas Bearings, JPL Letter Report No. 3," Letter Report No. 3, Jet Propulsion Lab., Cal. Tech., Pasadena, Calif., ORDCIT Project, Contract No. DA-04-495-ORD 18, Dept. Army. Ord. Corps.

Previous issues of these letter reports were not numbered. This report contains excerpts from Combined Bimonthly Summary No. 68 and deals with semi cylindrical and complete journal bearings. As in all reports of this group, curves of experimental and theoretical results are given.

166. "Gas Bearings" JPL Letter Report, August 14, 1958, 4 p.

This report outlines: (a) an analytical study of gas bearings. (b) an experimental study for the purpose of evaluating the theoretical findings and of establishing additional data for the design of gas bearings, and (c) the design of a first test fixture which will permit accurate measurements of the pertinent data of pad, step, journal, spherical and conical bearings.

167. "Gas Bearings, JPL Letter Report No. 4," Jet Propulsion Lab. Cal. Tech. Pasadena, Calif., Feb. 18, 1959, NASA Contract No. NAS w-6:

The work covered deals with the load carrying capacity, clearance, and gas flows of externally pressurized gas lubricated journal bearings.

168. "Gas Bearings" JPL Letter Report No. 5, June 15, 1959, 7 p.

This report includes excerpts from Research Summary No. 2 on "Experimental Investigation of Complete Journal Bearings" and from Research Summary No. 3 on "Spherical Bearings".

The total flow of air was determined by means of a variable-area type orifice meter in the manifold feed line to the radial and thrust bearing plenum. Gas flow rates were measured at no-load and closure load for plenum pressures up to 40 psig.

On spherical type air bearings, a more accurate analysis of some of the significant parameters was attempted. In this analysis the effect of compressibility of gas lubricant was considered.

169. "Gas Bearings 1. Gas Lubricated Spinning Spheres. 2. Friction Losses of a Spinning Sphere" JPL Research Summary No. 36-3. Vol. 1, Part 1, June 1960, pp. 76-78.

While previous studies (RS 3, 5, and 6) investigated the static performance characteristics of pivot-type spherical gas bearings under load, the present study presents results of an investigation on gas-floated spinning spheres. The applications of the latter are in gyro instrumentation and attitude control applications.

It is shown how a spinning sphere which may be hollow or solid is supported by a number of pressure pads which are supplied with a compressed gas through orifices.

Theoretical calculations of friction loss, drag (maximum, minimum and average drag) are given. Contribution of each pad to the total friction moment is shown to depend on its location relative to the spin axis.

170. "Gas Bearings 1. Multiple Orifice Journal Gas Bearings" JPL Letter Report No. 6, August 15, 1959, 5 p.

This report summarizes the results of tests extending the experiments outlined in RS 1 and RS 2.

Clear cut figures and tables show: Gas flow pattern of unloaded and loaded journal bearing in various areas of the bearing; load test at 24 psig plenum pressure; gap height vs. load for complete journal bearing; stiffness of journal gas bearing; circumferential pressure profiles of complete journal bearing; axial pressure profiles of complete journal bearing; load-

carrying capacity of complete journal bearing; gap height as function of pressure for complete journal bearing; total gas flow through complete journal bearing; and gap height as function of load with outer orifices sealed.

It is concluded that the performance of the multiple orifice journal bearing may be closely approximated by assuming constant pressure between the two inner rows of orifices and one-dimensional axial flow in the gap from the orifices to the ends of the bearing.

When the outer rows of holds were sealed off the load carrying capacity was only 58% of the theoretical maximum, compared with 72% with all four rows open. With the inner rows of orifices sealed off, the lift of the bearing is even slightly lower.

The spring rate of the bearing was 91,000 lb/in. with all orifices operating, while it showed only 77,000 lb./in when outer orifices were sealed off.

171. "Gas Bearings. 1. Spherical Bearing with a Recess" JPL Letter Report No. 8 Dec. 15, 1959,1 3 p. NASA Contract No. NAS w-6

This is a study of pressure profiles developed in spherical bearings with a recess (or step) in the socket. Their high load Capacity makes them of considerable practical interest.

To verify the theoretical findings, pressure profiles of a spherical bearing with a recess of $2\theta_0 = 60$ degrees in a hemispherical socket of R = 0.56365 inch were experimentally determined by means of test fixture (illustrated in Letter Report No. 7).

Pressure taps were provided at $\bar{\theta} = 0$, 15, 27.5, 52.50, 67.5 and 82.5 degrees and connected to pressure gages. Profiles were measured at plenum pressures of 40,24 and 8 psig. respectively.

The measured values, compared with the theoretical profiles, showed good correlation. The results of load tests for plenum pressures, as well, correlated satisfactorily.

172. "Gas Bearing Research and Development Program at Stratos" Stratos Div. of Fairchild Corp. Tech. Report 340, Feb. 5, 1960, 15 p.

The report discusses briefly the past, present and future programs of research on gas lubrication at Stratos.

The emphasis lies on (1) air cycle machinery and (2) turbo-expander machinery. It is claimed that the air cycle machine demonstrated great endurance. Some 400 hours of running time up to 56.000 rpm showed no signs of wear on the bearings. Advantages and disadvantages, and remedies envisaged in the future, of the turbo-expander machinery are discussed.

173. "Gas Bearings in Tensil Testing" Materials Research Digest, April 1961, p.3 (TID 3026 OTIE AEC)

In equipment developed at the Southern Research Institute for the evaluation of the true stress-strain properties of brittle materials at temperatures up to 5000F, nonuniaxial loading has been eliminated due to the use of gas bearings.

Preliminary data indicate that the gas bearings have a significant influence in reducing any bending in the specimen. The coefficient of friction acting through the bearings on the specimen is less than $5 \times 10^{-7}$. The resulting bending stress distortion in the specimen is less than 0.2 psi.

With gas bearings in operation, the average value for room-temperature ultimate strength of some standard-size graphite specimens with a thin ceramic coating was increased from 1737 to 3130 psi, an increase of about 80%.

In earlier tests with identical specimens using precision equipment and careful procedure, but without gas bearings, and average room-temperature ultimate strength of 2438 psi was observed. By comparison, the data recently obtained using gas bearings (3130 psi) show an increase in ultimate strength of 28.4%. A few high-temperature pulls have been made and approximately the same percentage increase in ultimate strength is evident at temperatures up to 4500 C. From post inspection of the specimen, the elongation may be as high as 3%. This ductility is further indicated by strain cracks in the broken specimens..

Each specimen was examined visually after rupture. Those pulled with the gas bearings were found to have a perpendicular cone-shaped type of break, which is indicative of pure tensile loading. Without gas bearings, rupture lines were nonperpendicular, indicating the presence of bending stresses.

174. "Gas Floated Spheres". JPL Research Summary No. 36-6, Vol. 1, October-December 1960, pp. 14-17

How the viscous flow solution of the Navier-Stokes equation could be applied to the flow through an externally pressurized spherical gas bearing which is fed by a centrally located single orifice was shown in the previous RS Nos. 3 and 5. Previously, a solution was obtained for the case of $\theta_1 = 90^\circ$ (the partial arc of the spherical bearing) and pressure profiles for various eccentricity values $\epsilon$ were presented.

In this report the solution has been extended to any value of $\theta_1$ less than $180^\circ$. Pressure profiles, load carrying capacity, and mass flow curves for the case of $\theta_1 = 60^\circ$ are presented. Bearings of this angular size have many engineering applications because of their large inherent angular operating range.

Tables show pressure profiles for spherical gas bearings at various eccentric positions; load carrying capacity of spherical gas bearings; gas weight flow rates; and pressure profiles for spherical gas bearing.

175. "Gas Lubricated Bearings-Design, Manufacture, Application," Engineering, Nov. 2, 1956.

Gas lubrication, which has recently undergone considerable development under the stimulus of the atomic energy programs, may well have applications to half a dozen other branches of engineering, and this is borne in mind by the authors of a paper "Principles and Applications of Hydrodynamic-Type Gas Bearings," presented at the Institution of Mechanical Engineers on October 26. The authors, Mr. G. W. K. Ford, Mr. D. M. Harris and Mr. D. Pantall, are all members of the United Kingdom Atomic Energy Authority. The call for gas bearings arose from the need to install moving parts within enclosed gas circuits where contamination of the gas is undesir0 able, the parts themselves are largely inaccessible and the formation of oxide films is impossible; this occurs in gas-cooled reactors such as those at Calder Hall. In addition, pumps for liquid metals, which may be at high temperatures, require a lubricant that does not deteriorate under the action of heat and will not contaminate the metals being pumped; bismuth, which may serve as a solvent for nuclear fuels in future reactors, is chosen by the authors as an example. However, high temperature, gas circuits, inaccessibility, particulate matter in suspension, and the need to exclude contaminating materials are requirements not unique to atomic engineering. To place gas bearings in the context of other applications, the authors outline their features and limitations, and name some other fields of engineering-machine tools and chemical industry for example- in which they may be used. The paper is concerned mainly with hydrodynamic as distinct from hydrostatic bearings and covers both thrust and journal types. Parts of it are reprinted below, but specialized data and calculations are omitted. (Auth)

176. "Gas Lubricated Bearings" Mech. Engng. Vol. 82, No. 2, Feb. 1960, pp. 92-93.

This article is a condensed review of the paper "General Review of Gas Bearings", by D. D. Fuller, which was presented at the Symposium on Gas Lubricated Bearings, Oct. 26 28, 1959, Washington, D. C.

The main topics reviewed are: hydrodynamic bearing; hydrostatic bearing; advantages of gas-lubricated bearings; areas of application; operating characteristics; instabilities;

potential of hydrostatic bearing; "micro-aerodynamics; and"air hammer".

The importance of gas-lubricated bearings is emphasized both for their use in the national defense and in areas of industrial activity.

177. "Gas-Lubricated Bearings Meet Special Needs of N-Plant"
Nuclear Energy, Vol. 14, No. 144, May 1960, p. 220.

Design of circulators and pumps for nuclear stations created unprecedented problems of breakdown of lubricants under radiation, and danger of escape of lubricant which had itself become radio-active. The solution was to use gas-lubricated bearings which permited design of electrically driven centrifugal circulators and pumps which could be assembled clean, dry, and enclosed, and installed completely sealed from the atmosphere. Hydrostatic and hydrodynamic gas bearings are described.

178. "Gas Lubricated Bearings, I. Slit Type Journal Gas Bearing"
JPL Research Summary Vol. 1, No. 36-4, Aug. 1960, pp 38-40.

A journal bearing is described in which the rows of radial orifices are replaced by narrow radial slits acting as viscous flow restrictors. It was designed with four slits of 0.005 inch width through which the gas is fed from the plenum to the bearing gap.

A total of 24 pressure taps with an equal spacing of 15° each was provided in the plane of one of the slits for the purpose of measuring circumferential pressure profiles.

Circumferential profiles of the slit type bearing and the profiles of the orifice type bearing are discussed, and the flow rates of the two types of bearings are compared. The slit type bearing is shown to be more advantageous. It is noted that turbine torques could not be observed in the operation of the slit type bearing.

179. "Gas Lubricated Bearings 1. Slit type Journal Gas Bearings"
JPL Research Summary No. 36-5, Vol. 1, Oct. 1960, pp. 28-29

The article summarizes results of further tests on a gas lubricated journal bearing in which narrow slits, instead of small orifices, serve as automatic pressure regulators between the gas supply plenum and the gap.

Stiffness and gas consumption of slit-type gas-lubricated journal bearings were measured and determined.

Visuliazation of the gas flow pattern in the bearing gap was accomplished by coating the shaft surface with a thin film of fluorescent oil and photographing it in ultraviolet light after exposure to the gas flow. Gas Flow patterns under load and 90° from load plane are shown.

180. "Gas Bearings 1. Theoretical Pressure Profiles. 2. Experimental Results" JPL Letter Report No. 7, Oct. 15, 1959, 5 p. NASA Contract No. NASW-6.

This report continues the analysis of spherical gas bearings with external pressurization (Research Summary No. 3). It corrects errors contained in RS 3.

It also gives results of an experimental investigation of pressure profiles which was undertaken concurrently with the theoretical analysis.

A hemispherical socket with a radius R = 0.56375 inch and an orifice of 0.004 in. diameter was built, which could be pressurized from a plenum chamber.

Pressure profiles for various conditions of load and eccentricities, and for different plenum pressures, were determined.

181. GERARD, P. L., "Combined Fluid Bearing and Mechanical Bearing for Gas Turbine Engines," U. S. Patent 2 623 353, issued 1952.

In a gas turbine application, the inventor uses rolling element bearings as an auxillary "standby system" since failure in the gas bearing external pressurization system is always a possibility.

182. GERARD, P. L., H. SERRANNE, "Fluid Bearing," U. S. Patent 2 660 484, issued 1953.

The inventor notes the disadvantage incurred by the use of a large volume recess when employing externally pressurized gaseous lubricants. His suggestion is to use grooves to outline various geometrics having the same area and perimeter as the chosen recess. The effect of this change is to reduce the tendency towards vibration.

183. GERARD, P. L., "Fluid Pressure Bearing," U. S. Patent 2 634 176, issued 1953.

When a rotating rotor becomes unbalanced through loss of a turbine blade or other cause, the centrifugal forces set up carry it close to the bearing walls and the shaft performs a kind of "whirl".

To combat this potentially dangerous condition, the inventor places a one way valve in the path of the orifice leading to each bearing recess. When the shaft approaches a recess, the fluid escape area is decreased. The pressure in the chamber builds up, causing the one way valve to close and preventing leakage except through the decreasing escape areas. Since the pressure continues to build up, the necessary counterbalancing force is thus set up.

The patent mentions water as the fluid to be used. Sixsmith uses a somewhat similar system for gases but with a restriction placed in the path of flow through the evacuation chambers.

184. GERARD, P. L., "Improvement in Fluid Bearings," Great Britain Patent 685 871, issued 1952.

The device described is a modification to improve the performance of a gas bearing. It consists of mounting a self-aligning rolling element bearing on a shaft and using a sleeve, press-fit on the outer race, to act as the journal member of a gas lubricated bearing. In the event of a lubricant failure through overload or other cause, the outer race of the rolling element bearing is restrained but the inner race and shaft are free to rotate.

185. GERARD, P. L., "Le Palier Fluide (The Fluid Bearing), "Memoires de la Societe des Ingenieurs Civils de France, Vol. 102, No. 2, Feb. 1949, pp. 106-134. Translated by A. Talis, Edited by E. B. Sciulli, Franklin Institute-Laboratories, Phila., Pa., Sept. 1957. Note: This same reference appears under similar title in other publications.

The reference contains a short history of externally-pressurized fluid bearings, noting their advantages and also some of their short-comings. Mention is made of several well-known devices which employ these bearings and a list given of possible applications to other machines. Under the advantages, Gerard notes the low, almost zero, starting friction one gets with these bearings, and the relatively low power requirements for their operation. In an extract from Planiol's work is included a comparison of the coefficients of friction of rolling element bearings ($1.5 \times 10^{-3}$), hydrodynamic bearings ($1.1 \times 10^{-3}$), precision watch jewel bearings (0.2) and a pressurized air-lubricated bearing ($2.6 \times 10^{-6}$).

A brief mathematical treatment, using the electric analogy, is given to the flow of fluids through two constrictions in series. The effect of various parameters such as chambers, flow, etc. are treated theoretically and appropriate curves and tables shown.

The main purpose of the paper is to describe Gerard's multi-pad versions of the fluid bearing which have a "self-centering ability." A description is even given of a rather drastic test of this ability in which a grinding wheel is deliberately unbalanced in order to observe the behavior of the bearing. Despite the strong vibrations transmitted to the grinding machine, the results of the grinding remained fairly good, indicating that the axis of the grinding spindle had turned (true) about an axis of rotation off-center by 0.02 mm. (In this demonstration oil was used as the lubricant.)

186. GESSNER, E., "Nomograph for Designing Gas Nozzles and Orifices," Product Engineering, Oct. 1956, pp. 141-143.

This nomogram solves problems relating to nozzles and orifices used as flow controlling devices for compressible fluids. Pressure drop can be found if the weight of flow and diameter are known for a particular upstream pressure. While drawn up for aircraft and missile problems, with flow correction for gases other than dry air, the nomogram may be applied to air conditioning and industrial problems.

Basis of nomogram is flow weight equation representing thermodynamic relationships for the ideal situation, and corrections are added for various non-ideal configurations. A coefficient accounts for relative difference in efficiency between nozzles and orifices. (Auth)

While it is true that this paper does not deal with gas bearings as such, it does contain usable information concerning nozzles and orifices which are an integral part of most externally pressurized gas bearings. While the theory and the requisite equations are available in many textbooks, nomographs of this type are not. The nomograph is included for its value as a convenient labor saving device.

187. GETTINGS, H. "Ceramic Gyro Ten Times More Accurate" Missiles and Rockets, Vol. 6, No. 23, June 1960, pp. 22-23

This is a news item concerning a new space-guided gyroscope developed at Minneapolis-Honeywell. It is similar to Honeywell's MIG except that the spin-motor, bearings, and gimbal are all made of gem-hard aluminum oxide ceramic.

In the new unit the ceramic shafts of the spin-motor serve as bearings, riding in ceramic "races" lubricated by a helium-gas film o.000025 in. thick. The gas film - virtually friction free - is under pressure that effectively makes it stiffer than the steel ball bearings it replaces. It is claimed that bearings underwent thousands of starts and stops without detectable wear.

Honeywell contends that the use of ceramics in critical parts limits bearing wear caused by starting and stopping.

According to Honeywell, in the ceramic gas bearing gyro the balls and retainers are eliminated, viscous damping is substituted for hysteresis damping, deformations due to thermal expansion disappear, and vibration or bearing noise is decreased by a ratio of 30 to 1.

188. GORDON, K. M. "Gas Bearings .. Part II, Aid in High Speed Torque Determination" MPB Engineering News, Vol. 6, No. 5, Sept. 1960, pp 1-2.

An instrument designed to measure the friction of ball bearings, by means of an air bearing, is briefly described.

The device consists of a cylindrical rotor carried at its upper end by the test ball bearing and guided radially at its lower end by an air bearing. Means is provided to bring the rotor up to a high rotational speed by air jets and then it is allowed to coast. Slots on the rotor are so arranged that the rotor chops a beam of light directed toward a photo-electric tube with a frequency proportional to its speed of rotation.

In operation, the rotor is brought up to approximately 40,000 rpm by the air jets and then is allowed to coast. The number of pulses received by the photocell is recorded over a one second period every other second by means of an electronic counter.

This air bearing has a diameter of $1\frac{1}{4}$", a height of $\frac{1}{2}$" and a radial clearance of 0.002". The torque at 10,000 rpm works out to be approximately 1000 mgmm.

189. GOTTWALD, F., R. VIEWEG, "Berechnungen und Modellversuche an Wasserund Luftlagern (Calculations and Model Tests on Water and Air Bearings)," Zeit. Angew, Physik, II Band, Heft II, 1950, pp. 437-443.

Most of the contents of this paper are contained in other papers by Gottwald which have been translated into English. Some of the other papers contain entire paragraphs lifted bodily from this one.

190. GOTTWALD, F., "Computations and Measurements on the Air Bearing," Archive 16/15, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground. Md., 1943.

An analysis for a conical bearing with compressibility taken into consideration, shows that no substantial difficulties arise when air is used as the lubricant instead of water; the load capacity even increases at a minor rate. The volume of air flow

is smaller than the value resulting from an estimation using the viscosity ratio between air and water. The regulating orifices or capillaries used for bearing stabilization may have practically the same dimensions as in water bearings. Practicable operating conditions are obtained when the bearing air pressure is divided between regulating point and housing gap in the ratio 1 : 1.

The bearing supply pressure must be adjusted to the external pressure. For constant load the relative pressure drop must also be constant if the same bearing gap is to be obtained. With decreasing external pressure the volume of flow remains practically constant, whereas the necessary air mass flow is respectively decreased.

A few measurements on a test bearing confirmed the correctness of the computations. (Auth)

This is but a part of a report on bearing devices. The work was done in Germany during World War II.

191. GOTTWALD, F., "Proposal for an Air Supported Course Gyroscope," Archive 16/16, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

After a critical discussion of the use of different kinds of bearings for the suspension of gyros, an arrangement is suggested which has small friction since it is an air bearing, and furthermore which avoids the unbalanced moments caused by bearing clearance. (Auth)

This report contains the reasons for building an experimental model (course) gyroscope which is air supported. Previous work by the same author leading up to this decision was also a part of this investigation of low-friction bearing devices.

192. GOTTWALD, F., "Tests on Air Supported Course Gyroscope," Archive 16/17, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

In a previous report, the author proposed an air-supported ball (course) gyroscope to be provided with a compensated universal suspension. Subsequently, experimental models were built and tested. This report covers those tests and gives the conditions under which the gyro maintains the prescribed precession limit. Although the author determined that the use of this type of device was feasible, he did not complete his work at this time. Since this is only one of a series of reports, it contains only a relatively small amount of information.

193. GOTTWALD, F., "Wasser-Luftlager mit Druckshmirung (Water Bearings and Air Bearings with Pressure Lubrication)," BuShips Translation 593, Office of Technical Services, PB 121405.

This paper covers part of the work this author did during World War II. Here the author summarizes the feasibility study on externally-pressurized water and air lubricated bearings. As in his previous work, the author suggests that air-lubricated bearings can be used in gyroscope compasses.

194. GRANEEK, M. and J. KERR "Air Bearings - Research and Applications at National Engineering Laboratory, Scotland." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., October 26-28, 1959, pp. 71-91.

A description is given of several items of equipment, incorporating externally-pressurized air bearings, developed at the Mechanical Engineering Research Laboratory, East Kilbride, Glasgow. The applications have been mainly to high precision measuring devices requiring frictionless supports and constraints. An experimental program has been carried out on flat air bearings which has led to the derivation of empirical formulae relating design parameters.

With self-acting air bearings some preliminary measurements have been made of film pressure distribution and eccentricity in journal bearings and the results have been compared with theory.

195. GRANEEK, M., H. L. WUNSCH, "Testing the Performance of Precision Ball Bearings." The Engineer, Vol.178, Nov. 26, 1954, pp. 695-697.

Little information is available on the performance of high-precision ball bearings of small diameter when operating at very high speeds. A machine has, therefore, been developed which provides a continuous measurement of frictional torque at speeds up to 50,000 r.p.m. of small bearings under defined axial and radial loadings. This article is primarily concerned with the development of the testing machine. But the ultimate object in view is the correlation of the dimensional accuracy of the bearings with overall performance. The torque-speed characteristics of particular types of bearing will also be investigated. (Auth)

The authors describe a test machine which uses externally-pressurized air bearings. These include two main journal bearings and a thrust bearing for the test shaft as well as two journal and two thrust bearings for the drive motor. Exhaust air from the motor bearings, passed over the stator laminations, aids in cooling. One other air bearing, a hydrostatic "Floating" bearing, is used to apply the radial loads. Because of its designed

purpose the test shaft had to be dynamically balanced to a high degree of accuracy. Maximum test speeds of 50000 rpm were attained with the unit. Although the bearings are described, there is insufficient information given, theoretical or otherwise, to permit designing them.

196. GRINNELL, S. K., "A Study of Pressurized Air Bearing Design - Steady Loading - No Rotation," M. S. Thesis, 1954. MIT Department of Mechanical Engineering, Cambridge, Mass.

In one phase of the investigation simulation is used to determine the optimum ratios for design parameters used in air journal bearing design, minimizing mass flow rate and maximizing stiffness and load-carrying ability.

The pressure distribution and mass flow rate for one dimensional compressible fluid flow between closely spaced flat plates were studied as a basis preliminary to an understanding of the flow in a bearing.

Theoretical expressions for the pressure distribution and mass flow rate are developed analytically and verified experimentally. The simple Hagen-Poiseuille capillary flow theory was found to be good for predicting the pressure distribution if the flow path length to height ratio is greater than 1000. For smaller values the one dimensional compressible flow with friction theory of Shapiro correlates well with experimental mass flow rate, friction factor and pressure distribution. (Auth)

This 112 page thesis represents an extensive amount of work; among its contents are 41 illustrations, 11 appendices and numerous references all applicable to the subject chosen. Theoretical analyses are made for one-dimensional flow of a compressible fluid between flat plates, constant area flow of a perfect gas with friction and capillary type flow with and without momentum effects included. The design of test equipment and instrumentation are discussed and the results compared with the work of other authors where possible.

197. GRINNEL, S. K., H. H. RICHARDSON, "Design Study of a Hydrostatic Gas Bearing with Inherent Orifice Compensation," Trans. ASME, Vol. 79, No. 1, Jan. 1957, pp. 11-22.

A hydrostatic gas bearing can provide shaft support with very low friction in high-speed devices such as centrifuges and gyroscopes and in precision static devices such as dynamometers. For comparable load conditions, the friction torque required to rotate a hydrostatic bearing is from 100 to 10000 times less than the friction torque required to rotate ball or hydrodynamic oil bearings. This paper presents information directly applicable to

to designs with optimum performance characteristics for hydrostatic gas bearings with inherent orifice compensation. An analytical and experimental study of a simplified model of the basic unit of which the bearing is composed and a similar study of a complete journal bearing lead to a readily usable design procedure for the hydrostatic gas bearing. The load capacity, or stiffness, and weight flow rate predicted by the design procedure are verified within 10 and 20 per cent, respectively, by experimental results obtained with an optimized bearing. (Auth)

A brief review of hydrostatic bearing development is first given and then three configurations are dexcribed after which the principles of operation of the authors' bearing are discussed. The simplifying assumptions made for analysis purposes were such that it became possible to build a simulation model consisting of square, flat, parallel plates with a single air inlet hole in one of them. The experimental results obtained with this rig are shown graphically in the text for the paper.

The analysis of the complete, full multipad bearing is made on the basis of one dimensional, laminar, isothermal, compressible flow. The resulting equations are then converted to yield dimensionless parameters with which to evaluate bearing performance.. The authors do not recommend extrapolation beyond the range of the parameters covered in the simulation.

198. GRINNELL, S. K., "Flow of a Compressible Fluid in Thin Passages," Trans. ASME, Vol. 78, No. 4, May 1956, pp. 765-771.

Pressure distribution and weight-flow rate can be predicted for laminar compressible-fluid flow in a thin passage by use of the methods presented in this paper. A simplified method can be used readily when the fluid forces due to viscous action predominate over those due to acceleration of the fluid. A more complicated trial-and-error method seems to be required for larger passages where, though the flow may be laminar, the momentum effects due to acceleration of the compressible fluid are appreciable. An experimental apparatus was used to examine the validity of the analytical work. Experimental pressure distributions agree within a maximum deviation of 10% with the theoretical distributions predicted by both the comprehensive and simplified theories. Experimental weight-flow rates agree within a maximum deviation of 50% with predictions of the simplified theory. Dimensionless plots of pressure distribution are presented with experimental curves of flow rate versus pressure ratio for various ratios of passage length, L, to passage height h. These plots, together with simple equations, have been prepared for direct use by the designer. (Auth)

Much of the work included here is contained in the author's MS Thesis. Hughes points out in the discussion at the end of the paper that for the flow of a compressible fluid in

thin passages, an adiabatic treatment yields results identical with the isothermal solution, and, in fact, the adiabatic treatment shows that the isothermal solution is the only possible one compatible with energy conservation.

199. GROSS, W. A., "A Gas Film Lubrication Study, Part 1: Some Theoretical Analyses of Slider Bearings," IBM Journal of Research and Development, Vol. 3, No. 3, July 1959, pp. 237-249.

The Reynolds differential equation describing flow in a compressible lubricating film is developed. Important characteristics of such films are determined directly from the Reynolds equation. Pressure, load, velocity, and geometry characteristics are presented for many compressible slider bearing films based upon computer solutions of a Reynolds difference equation as derived in a companion report. Another companion report cites experimental verification of computer solutions and describes experimental techniques. (Auth)

Parts II and III of this study are authored by W. A. Michael and R. K. Brunner et al., respectively.

200. GROSS, W. A. "Film Lubrication. III. Basic Hydrodynamic Relations" IBM Res. Laboratory, San Jose, Calif., Tech. Rept. RJ-RR-117-3, May 22, 1958, 27 p.

This is the third of a series of reports which deal with the theoretical aspects of hydrodynamic film lubrication. It is designed to aid understanding of gas lubrication.

First, the author analyses the Navier-Stokes momentum equations for a laminar Newtonian fluid. They are equations of motions, generally applicable for laminar flow save in regions where the divergence or dilatation of the fluid is very great. These equations list velocity in terms of body forces, density, viscosity velocity gradients, and pressure distribution.

To determine the relationship between density, pressure, viscosity, and velocity, additional equations are introduced for the particular cases of gas and air as lubricants.

Further, after establishing boundary conditions, the author combines the momentum equations with the continuity relation equation in order to give the Reynolds equation a single differential equation relating pressure, density, velocities, and film thickness.

201. GROSS, W. A., "Film Lubrication, IV Compressible Lubrication of Infinitely Long Slider and Journal Bearings," IBM Research Paper, RJ-RR-117-4, June 25, 1958.

This is the fourth of a series of reports which deal with the theoretical aspects of hydrodynamic (self-acting) film lubrication. The aim is to aid understanding of the properties of gas lubrication. (Auth)

This rather short paragraph introduces a 105 page paper which lists 24 references including ones by W. Froessel, A. G. M. Mitchell, A. A. Raimondi and J. Boyd, G. I. Taylor, Y. Katto and N. Soda, V. N. Constantinescu and others. The work of these men is woven into a smooth, well developed comprehensive technical paper covering many phases of gas lubricated bearings.

202 GROSS, W. A. "Film Lubrication -V. Infinitely Long Incompressible Lubricating Films of Various Shapes" IBM Research Lab., San Jose, Calif., Rpt. No. RJ 117-5, October 10, 1958, 81 p.

This is the fifth of a series of reports which deal with the theoretical aspects of hydrodynamic film lubrication. The aim is to aid understanding of the properties of gas lubrication.

It presents analyses of lubricating films in which either turbulence or cavitation is present. The author says that both liquid and gas films may become turbulent during high-speed operations. In addition, a liquid lubricating film is susceptible to cavitation. Hence, although the incompressible film results may always be applied to limiting gas films (having small bearing numbers, $(G = \mu UB/P_a h_m^2 \rightarrow 0)$ (Note: G is currently being replaced by the symbol $\Lambda$), they may not always be used directly for liquid films, because of the cavitation phenomenon. An alternative derivation of the Reynolds Equation is provided for incompressible constant viscosity films which have negligible inertia. Application is made to several infinitely long slider and journal bearings having incompressible films.

203. GROSS, W. A. "Film Lubrication, VI, Effects of Heat, Deformation, Fluid Viscosity and Density upon Infinitely Long Liquid Lubricating Films" IBM Res. Laboratory, San Jose, Calif., Tech. Rept. RJ 117-6, April 6, 1959, 98 p.

This report presents approximate analyses for studying the effects of lubricant inertia, and heat generation on oil-lubricated slider bearings and journal bearings. The variation of viscosity as a function of pressure through the fluid film is studied for slider bearings and concentric cylinders, as well as the temperature variations across the film under adiabatic conditions. The results are for incompressible fluids but are applicable also to gas-lubricated bearings with low compressibility numbers.

204. GROSS, W. A. "Film Lubrication. VII. Finite Incompressible Lubrication Films" IBM Res. Laboratory, San Jose, Calif., Tech. Report. RJ 117-7, June 30, 1959, 131 p.

This report deals with certain aspects of fluid film lubrication. Several analytical methods (along with their restrictions) are presented for the solution of Reynolds equation, viz., the variational method using the calculus of variations, the perturbation method and the separation of variables method. Also presented are the electrolytic tank analogy and a numerical method using the Reynolds' difference equation. Solutions using these methods are presented for finite slider bearings and finite journal beearing of various configurations. Although the author includes the word "incompressible" in the title, the analyses presented are applicable to compressible fluid film lubrication. The analytical and test results shown for incompressible fluid films are applicable to compressible fluid films for bearings with low compressibility numbers.

205. GROSS, W. A. "Film Lubrication - VIII. Unsteady Bearing Films and Bearing Systems" IBM Research Lab., San Jose, Calif., Rpt. No. RJ 117-8, May 1, 1960, 89 p.

This is the eighth of a series of reports dealing with the theoretical aspects of fluid film lubrication. Unsteady, incompressible films which are both infinitely long and finite are examined. Results are given for both slider and journal bearing films and for bearing systems. The results are applicable to gas lubricating films when pressure changes are sufficiently small.

The presence of shaft flexibility does not significantly change the behavior of a complete uournal bearing film when velocities are well below resonant conditions. A steady whirl with $\alpha_t = 1/2\,\omega$ can be sustained with or without unidirectional loading. The effect of periodic loads is dependent upon the nature of such loads, but an orbiting frequency of half the amplitude of this low-frequenfy, self-excited whirl may be so low that it is difficult to observe. Large loading, large clearance ratio, and small slenderness ratio will tend to minimize the whirl amplitude in this region of operation.

Increasing speed will cause a resonant whipping of the journal when the frequency is about at the first system critical. This will not cause failure of balancing is adequate. Increasing speed results in a decreased amplitude until onset of half frequency orbiting at $\omega = 2\,\omega_n$. Amplitude increases here because of the available energy from the resonating shaft. With increasing speed, the film will pass through this resonance condition and the orbiting amplitude will decrease.

A unidirectionally loaded shaft may orbit at half the rotational speed such that the orbit does not enclose the bearing

center. If the speed is sufficiently high compared to the first system critical, it is apparent that a sharp jar could cause the system to commence orbiting about the bearing center with an accompanying large amplitude. Sensitivity to such jars decreases with increasing mass or load.

Nonlinear behavior of the amplitude and eccentricity must, of course, be expected. For example, large amplitude shaft whip may not occur until $\omega \geq 2\omega_n$. This is accentuated by increased forces due to increased mass or loading. Upon reducing speed, the whip may persist until $\omega < 2\omega_p$. The history of the disturbance becomes crucial. Therefore, phase plane representations can be of some value.

Although small slenderness ratio and low viscosity are desirable for increased stability at low speeds, the reverse is true for $\omega > \omega_n$. It has been tacitly assumed that the lubricating film is laminar. The increased frictional and pressure forces which accompany turbulent conditions may be advantageously used to increase stability. (Auth)

206. GROSS, W. A. "Numerical Analysis of Gas-Lubricating Films." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. D., October 26-28, 1959, pp. 193-224.

Numerical approximation methods are discussed. By the use of one of these methods, the Reynolds differettial equation for a laminar gas-lubricating film is replaced by a difference equation which is then applied to self-acting gas bearing films. A method of numerical solution of this difference equation is described and agreement between experimentally determined and computed data is discussed and presented in graphicll form. Detailed treatment is given the properties of self-acting plane, tapered land and step slider bearing films such as the effects of slenderness and film thickness ratios, and of driving surface velocity upon bearing load. Some friction and center-of-pressure results are also given. Consequences of changes in tangential surface velocity and mimimum film thickness upon pivoted sliders are also shown.

207. GROSS, W. A. "Steady Performance Characteristics of Gas-Lubricated Bearings with Slenderness Ratio LID = Jl" J. Aerospace Sci. Vol. 27, No. 11, pp. 869-870 (Readers' Forum) Nov. 1960.

In a short note the author gives results on load, friction, and attitude angle for gas journal bearing films which have slenderness ratio (length/diameter) $L/D = \pi$. The author believes that these films are long enough to develop pressure profiles in the middle of the bearing which are comparable to those for infinitely

long bearings. They are short enough however to permit a convenient finite-difference solution.

By means of a digital computer using 24 X 12 grid points, solutions were obtained concerning the effect of eccentricity ratio and bearing number on load, friction and attitude angle for this bearing. The author gives credit for these solutions to W. A. Michael who programmed the Reynolds equation solution.

For computer evaluation, the Reynolds differential equation was replaced by a difference equation (as shown by W. S. Michael in IBM J. Res. Devel. Vol. 3, pp. 256-289, 1959). Continuity was imposed by requiring the pressure and pressure gradient obtained from the computer solution to be continuous.

208. GROSS, W. A. and E. C. ZACHMANOGLOU "Perturbation Solutions for Gas-Lubricating Films" Trans. ASME - J. Basic Engng. Vol. 83, Series D, No. 2, June 1961, pp. 139-144.

Perturbation solutions for large and for small bearing numbers are developed and applied to steady, self-acting, infinitely long, journal and plane-wedge films. Bearing films of this type develop load capacity as a consequence of relative surface motion. The solutions given here have validity for all ranges of geometrical parameters. Four-place accuracy in determining the load carried by a journal bearing is achieved. The plane-wedge film solution for large bearing numbers is complicated by the reduction in order of the limiting equation. A boundary-layer type analysis yields fairly accurate results. (Auth).

209. HAGEN, G. I., "Air Floating, a New Principle in Magnetic Recording of Information," Computers and Automation, Vol. 2, No. 8, Nov. 1953, pp. 23-25.

(Not available for review as of July 1, 1959)

210. HAGEN, H. W., "Bau und Berechnung Luflgelagerter Wellon (Design and Construction of Shafts Supported on Air Bearings)," Dissertation Technische Hochschule, Aschen, Germany, 1951.

The need for air lubricated bearings in modern technology is stressed. Early work on the theory involved is reviewed along with the few practical applications which had been made in this field up to 1948. Limitations of these early models are discussed. The principles of air lubrication are outlined in detail.

The author describes a bearing which he constructed to carry out a determination of its load capacity. In this section

he treats only radial bearings - the principles underlying their use and the calculation of static load capacities. Calculations of the theoretical maximum of the load capacity are made both rigorously and by a simpler method utilizing an analytical approximation. These calculations are made under the assumption that the axle is weighted so that it is exactly tangent to the bearing casing. Since this is true only of ideal geometrical bodies, a planimetric method is described which takes waves and roughness on the surface structure of parts into consideration. The results indicate that a calculation of the load capacity made by this method is approximately 20% lower than theoretical because of deviation of axle and bearing casing from the ideal form.

A method is next described for calculating the load capacity for any axle displacement by means of analytical approximation. These equations do not give the maximum load capacity, but they do allow the load capacity to be calculated as a function of axle displacement.

In making the calculations above, it was assumed that the weighting force caused a displacement parallel to the axle. This is generally true if two air lubricated bearings are used with a fairly large distance between them. However, in some cases it is more practical to use a single air lubricated bearing as a radial bearing. In such a case the weighting force is no longer in the middle, and this causes the axle to rock (tip) in the bearing casing. A method is presented for calculating this rocking (tipping) moment by analytical approximation. The result obtained theoretically agrees well with the value determined experimentally.

The total load capacity is made up of both static and dynamic elements. The dynamic load capacity can be calculated in the same manner as the hydrodynamic load capacity, taking into consideration the differences in physical constants between oil and air, especially the compressibility of the latter.

In the next section the principles of axial bearings are considered and their construction is described. Calculations are made to determine their load capacity and "value coefficient".

The use of air lubricated bearings in practice is described, along with methods to determine their coefficient of friction and their vibration. The relative merits of employing high-frequency motors or gas turbines to drive the axles are considered. One-and two-bearing polishing machines constructed by the author are described. From experiments conducted on them, both as polishers and borers, the author concludes that their usefulness has been established. Further improvemetts are suggested and other possibilities for the use of air lubricated bearings are considered.

211. HANDEN, D., "An Investigation of Air-Lubricated Shoes for High Density Magnetic Drum Head Applications," IBM Research Report No. RC-4, Jan. 1, 1957.

(Paper not available for review as of July 1, 1959)

212. HANSEN, P. D., "Flow of a Compressible Fluid in a Thin Pagsage," DACL Res. Memo No. 7401-2 MIT, Cambridge, Mass., 1957.

This work was classified as of July 1, 1959 and therefore unobtainable for review purposes.

213. HANSEN, S., "Fluid Bearing Mount," U. S. Patent 2 710 234, issued 1955.

A plurality of air pads are used to support the sphere for a stabilized platform. Pressurized air is supplied to some of the pads, and the other pads are evacuated. The "push-pull" effect keeps the sphere in the desired position. Extensions of the patent include changes in configuration from a sphere to truncated cones and eventually flat surfaces.

214. HARGENS, C. W., and D. A. KEIPER, "Tonometry-Challenge for Electronics", Digest of Intern. Conf. on Medical Electronics, July 1961, p. 77.

Newly deviced tonometers (instruments designed to measure the pressure within the eyeball) use an air bearing to support the moving element of the instrument. The holes in this bearing (which is one of the smallest examples of an hydrostatic air bearing) are about five times the diameter of a human hair. The bearing was designed and machined to these rigid specifications by the friction engineers of the Franklin Institute Laboratories. The instrument will be used for an experimental glaucoma - detection system.

215. HARRISON, W. J., "The Hydrodynamical Theory of Lubrication with Special Reference to Air as a Lubricant," Trans-Cambridge Phil. Society, Vol. 22, 1913, pp. 39-54.

The paper is made up of two sections, the first of which deals with the hydrodynamics of incompressible fluids. Here, Harrison, in attempting to simplify the work of Reynolds and Petroff, limits his analysis to the case of a complete cylindrical bearing (of infinite length). Making the usual assumptions, he arrives at equations identical to Sommerfeld's with somewhat less effort.

Analyzing the forces (and moments) in the system he shows or concludes that Kingsbury, with the air-bearing, erred by measuring the friction on the journal and saying it was that of the bearing. From his derived expressions, Harrison then calculates the pressure distribution in Kingsbury's air bearing and compares the results with the experimental data. It was this comparison which pointed out the need to consider the compressibility of the gas lubricant.

The second section of the paper contains the derivation of the equations of hydrodynamics considering the compressibility of the lubricant. (The flow is assumed to be isothermal.) These equations are then applied to the cylindrical journal bearing and integrated numerically by Runge's method (not shown). In a series of curves (for three speeds) it is shown that the new equations predict Kingsbury's experimental results much more accurately than do the equations neglecting compressibility. An analysis is also included for the case of compressible fluids between inclined planes. The conclusion drawn from Harrison's work is that for high rotational velocities, the compressibility of air should be included in the analysis of hydrodynamic bearings.

A classic, with more than just historical value, this paper contains the original work on the use of compressible fluids as lubricants.

216. HAYNES, L. and D. J. JAY,"Sliding on Air", Paper presented at the SAE Annual Meeting, Detroit, Mich., Jan. 14, 1960, Paper No. 133B, 5 p.

Possible applications of Levapads are discussed. Since air is used as the lubricant, similarities and differences between conventional air-lubricated bearings and levapads are briefly outlined.

The air velocity is less than 100 ft./sec. in air bearings, but reaches nearly acoustic velocity in levapads. Therefore, the Reynolds number is materially higher in the levapads, and accordingly, they have turbulent flow as opposed to the laminar flow of conventional air bearings. For laminar flow, under isothermal conditions, such as is common with conventional air bearings, the rate of pressure drop can be assumed linear.

The calculation of load-carrying capacity for the center is identical for levapads and for conventional air-lubricated bearings. Since the pressure is constant, the force is merely the product of the area and the pressure, and therefore $F_C = \pi r_i^2 P_i$ . This is where the similarity ceases.

For a levapad, since it operates with turbulent flow, even under isothermal conditions the pressure drop in the ring is no longer linear. A study of levapad vibrations provides another example of how levapads differ from conventional air bearings; a levapad designed at random will have a tendency to vibrate under most conditions of loading and air feed.

217. HEICHERT, H. S., "Air as a Lubricant," Engineering News Mar. 8, 1900, pp. 158-159.

Brief article describing the work of Kingsbury in 1897.

218. HEINRICH, G., "The Aerodynamic Bearing," (In German), Machinenbau u Waemewirtschaft 7, 199-35 (1952). H.28368 (HU) A.E.R.E. Harwell, Nov. 1956. In U. S., 7168 AEC tr 2920. Translated by R. Todd.

The double sided, annular tracked bearing was dealt with and formulae for the average bearing pressure and the energy necessary for the compressor were derived. By means of a numerical example, it was shown how the quantities corresponding to a minimum energy requirement are determined. (Auth)

219. HEINRICH, G., "The Theory of the Externally-Pressurized Bearing with Compressible Lubricant." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 251-265.

For economical design of externally-pressurized, gas-lubricated bearings the compressibility of the lubricant has to be taken into account.

From the Navier-Stokes equations in combination with the equation for isothermal change of state and the continuity relation for the compressible lubricant, the differential equation governing the pressure distribution in the lubricant film results..

Special emphasis is put on the solution for the journal bearing of a cylindrical shape, considering turbulent flow conditions whihin the lubricant supply lines.

By means of a dimensionless representation, the optimum conditions are derived to establish minimum power supply.

For maximum utility the analytical results are given in graphical form.

220. HEINRICH, G. and A. SLIBAR, "Gas-Lubricated Radial Journal Bearings" U. S. Patent 2,879,111, March 24, 1959, 4 p.

This invention relates to a radial journal bearing which employs as a lubricant a gaseous medium having the coefficient of viscosity $\eta\eta$ It comprises both a bushing and a shaft or journal within that bushing for operation below a predetermined load-speed ratio. This is a ratio between the mean load Pm per unit area and a speed at which adjacent surfaces of the bushing and journal have the relative velocity $C_u$ and which has the relative

roughness $z = \frac{t - a_o}{t}$

where $t$ is the mean difference between bore radius and journal radius and $a_o$ is the critical eccentricity or the displacement of the journal center required to cause linear contact between journal and bore. The invention provides a bearing of this type in which the value of $t$ as defined above and the journal diameter D are related to each other so that the dimensionless ratio

$$R = \frac{2 \quad Pm \cdot t^2}{3\pi \eta \cdot c_u \cdot D}$$

of the parameters influencing the carrying strength of the gaseous lubricant does not exceed the limiting value at which the linear contact between journal and bore begins at the predetermined load-speed ratio. The limiting value of the dimensionless ratio is a function of the relative roughness $z$ for each value of

$$X = \frac{L}{D}$$

where L is the effective length of the bearing, i. e. the length of the line of contact between journal and bore and D has the value defined before.

221. HENRIOT, E., E. HUGUENARD, "Les Grandes Vitesses Angulaires (High Rotational Speeds (Air Lubricated Top)), Revue Generale des Science Pures et Appliquees, Tome 38, No. 20, Oct., 1927, pp. 565-569. Le Journal de Physique et le Radium, Series VI, Tome VIII, Nov. 1927, No. 11, pp. 433. Also "Sur la Realisation de Tres Grandes Vitesses de Rotation, (On the Realization of High Rotational Speeds)," Comptes Rendus Vol. 180, May 11, 1925, pp. 1389-1392. (Presented at Session of April 6, 1925.)

The paper describes the development of an air-driven centrifuge in the course of which it became necessary to use an air bearing to reduce the friction sufficiently to attain high rotational speeds. According to Gerard, Huguenard, the co-author, was the inventor of the air-driven, air-bearing supported turbine.

222. "High Speed Air Bearing," National Research Development Corp. Bul., No. 9, Mar. 1957.

The NRDC Bulletin contains periodic reviews of inventions for industry. This particular issue mentions the bearings developed by Sixsmith.

223. HIRAYAMA, N., "Research on a Pneumatic Journal Bearing," (In Japanese) Trans. J.S.M.E., Vol. 19, No.78, 1953, pp. 13-16.

Assuming the fluid incompressible and viscous, the flow pattern in the bearing clearance of a practical pneumatic journal bearing is analyzed theoretically and pressure distributions are calculated. The plausibility is confirmed by experiments. (Auth)

224. HIRN, G., "Etudes sur les principaux phenomenes que presentent les frottements mediats et sur les diverses manieres de determiner la valeur mecanique des matieres employees au graissage des machines (Study of the Principle Phenomena which are shown by Friction Media and on the Manner of Determining the Mechanical Value (Viscosity) of Substances used as Lubricants for Machines)," Bulletin de la Societe Industrielle de Mulhouse, Tome 26, No. 129, 1854, pp. 188-277.

Mr. Hirn, speaking before an assembly, told how he found the "fluidity," i.e., the reciprocal of viscosity, to be that property of an oil or grease which determines its lubricating qualities and the relative coefficients of friction. It is this paper that mentions for perhaps the first time in print that almost anything, including air, can be used as a lubricant.

A rather lengthy dissertation, it is included here primarily because of its historic value.

225. HIRSCH, E. H., "The flow of Gas Through Porous Media in the Region between Molecular and Viscous Condition", Dept. of Supply, Australian Scientific Service, Weapons Research Establishment, Tech. Note ERD 70, Jan. 1960, 12 p. Also, NASA N84198.

Experiments are described on the flow of gases through porous Pyrex discs at pressures in the range of a few millimeters Hg. For air, hydrogen and carbon dioxide the specifc flow is found to be given by

$$Q = \frac{A}{\sqrt{MT}} + \frac{B}{\eta\sqrt{T}} + \frac{C}{\sqrt{M}}\left(1 - e^{-\frac{\beta}{\sqrt{T}}P}\right)$$

the significance of this result is discussed. (Auth)

226. HIRSCHFELDER, J. O., M. H. TAYLOR and T. KIHARA, "Viscosity of Two Component Gaseous Mixtures". University of Wisconsin, Theoretical Chem. Lab., Tech. Rep. No. 29, WIS-00R-29, July 8, 1960, AD-241,755, 16 p.

The conditions are found where the viscosity of a binary mixture of dilute gases either has a maximum or a minimum with respect to variations in the composition. A maximum in the viscosity is most likely to occur for a mixture of a polar and non-polar gas in which the viscosities of the pure components are nearly equal and their molecular weights are quite different. A minimum should occur for a mixture of two non-polar gases in which both the viscosities and molecular weights of the pure components are nearly equal. There are many experimental examples of maxima in the viscosity but up to the present time no cases have been discovered where the viscosity has a minimum. The maximum value of the viscosity and the mole fraction at which it occurs can be used to determine the energy of interaction between unlike molecules. (Author)

227. HOFFER, F. W., "Automatic Fluid Pressure Balancing System," U. S. Patent 2 449 297, issued 1948.

This is a rather lengthy patent which extolls the virtues of externally pressurized bearings, in particular those which embody the inventor's suggestion to use "Balancing zones" and "isolating grooves". A number of geometries or configurations are shown to which this zone and groove design can be applied. The term fluid is used continuously and pressures of 5000 psi are spoken of which generally indicates liquid lubricants. However, the inventor does not restrict himself and does make a number of specific mentions of using gaseous lubricants.

Like most patents, this contains no mathematical analyses or treatment. The discussion does contain many good practical design ideas among which are the use of orifice and the bearing sills to restrict or control the flow.

228. HONESS, W. T., "Air Bearing Thrust and Radial Supporting Bearing," U. S. Patent 2 617 696, issued 1952.

The inventor uses air as the lubricant in both thrust and radial support bearings for an air driven turbine. The inventor claims that because of the air bearings the unit can operate at high temperatures.

229. HOOKER, R. J. and D. W. JONES, "Design and Development of a Helium-Nitrogen Compressor with Hydrostatic Gas Lubricated Bearings" General Engineering Laboratory, Report No. 59GL 116, May, 1959, 46 p.

The design and development of a compressor for use in an in-pile loop at Hanford, Wash. is reported. This is the first time

known to the authors that hydrostatic gas lubricated bearings have been put to an application of this kind. The reason for using gas bearings was to fulfill the non-contamination requirement of the loop.

During the development testing of the four He-$N_2$ compressors there were over 160 hours of running time and more than 340 start-stop cycles accumulated. Inspection measurements of both journal and bearing surface have shown no dimensional change to indicate wear, scaring or other malfunctioning that would lead to eventual failure of either the radial or thrust bearing surfaces. In addition, the performance of both He-$N_2$ compressors exceeded the design specification in both flow and pressure.

The use of a gaseous lubricant and the design, construction, and testing of a hydrostatic gas-lubricated bearing has been accomplished as a result of this development project.

230. HUGHES, W. F., J. F. OSTERLE, "Heat Transfer Effects in Hydrostatic Thrust Bearing Lubrication," Trans. ASME, Vol. 79, No. 6, Aug. 1957, pp 1225-1228.

The limiting isothermal and adiabatic operating conditions of the hydrostatic thrust bearing have been investigated recently. However, the actual performance of such bearings is characterized by an intermediate situation in which heat transfer occurs in the lubricant and bearings. In this paper a simplified model is constructed for such intermediate situation, and it is found that the bearing performance is essentially isothermal at an elevated temperature. Expressions are derived for the temperature distribution, and the results of numerical examples are compared with isothermal and adiabatic calculations. Compressible and incompressible lubricants are considered. (Auth)

231. HUGHES, W. F., J. F. OSTERLE, "Temperature Effects in Hydrostatic Thrust-Bearing Lubrication," ASME Paper No. 56-LUB-11.

The hydrostatic thrust bearing is analyzed under adiabatic flow conditions for both an incompressible (oil) and a compressible (air) lubricant. Expressions for the pressure and temperature distributions, load capacity, and frictional torque are obtained. For the incompressible case the load capacity undergoes appreciable deviation from the isothermal behavior with variations in angular velocity. However, for the compressible lubricant, the load capacity differs only slightly from isothermal behavior and is nearly constant with variations in angular velocity. (Auth)

232. HUTCHINS, E. E., "Tests on the Pump Unit for the Mk I Uranium-Bismuth Loop (BERO), "AERE R/M 24, 1957, UKAEA Harwell, Berkshire, England.

This memorandum describes tests carried out to determine the characteristics of the centrifugal, induction-driven pump unit, built into the Mk I Uranium-Bismuth Loop which is to operate in BERO. Reference is also made to the apparatus employed for making the tests. (Auth)

Gas lubricated bearings were employed but there is little more than mention of them made in this report.

234. HUTTON, U. O., "A Tilting Air-Lubricated Piston Gage for Pressures Below One-Half Inch of Mercury" NBS J. Research, Vol. 63C, No. 1, July-Sept. 1959, pp. 47-57.

A description is given of a tilting dead-weight piston gage constructed at the National Bureau of Standards for ranges of differential pressure up to about 0.5 inch of mercury. A resolution of better than 1 part in a hundred thousand of full scale has been obtained by use of the tool makers sine bar method of angle measurement. The scale is a linear function of the sine. The instrument can be calibrated from basic measurements of length andwweight, is rugged, and may be constructed in almost any laboratory mechanical shop. Sources of possible errors in reading are discussed in detail. Comparative tests with certain other gages or manometers are cited wherein linearity was found to be within 1 part in 10,000 and agreement with 2.5 parts in 10,000. The uses of the gage are briefly discussed. (Auth)

235. "Improvements in the Rotor and Stator Construction of Gas Turbine Engines" Great Britain Pat. 867,600, May 10, 1961, 5 p.

This invention is directed to a rotor and stator combination employing air bearings as the sole means of rotor support during rotation.

According to the invention the rotor comprises a number of axially-aligned and axially-spaced wheels with flexible torque transmitting means interconnecting the spaced wheels for rotation together, and in which the rotor is supported by air bearings.

It also states that the stator surrounding the rotor includes vanes that extend inward in a radial direction, the inner periphery of each stator vane being formed to provide a continuous annular recess containing pressurized air to form air bearings for supporting the rotor.

236. "Improvements Relating to Lubrication Systems" Great Britain Patent 856,516, Dec. 1960.

A lubricating system applicable to high speed machinery is described. Turbine driven fluid circulating units used in the air conditioning systems of aircraft and other vehicles, in which

the rotating parts may turn at speeds of 50,000 to 100,000 rpm. or more, can find a useful application of this invention. The bearing lubrication system includes a rotating shaft carried by bearings in a casing, a lubricant reservoir formed in the casing and in annular lubricant pick up element which is mounted in the reservoir and surrounds the shaft, and which is capable of conveying lubricant, and pumping means for transfering lubricant from the interior of the pick up element to the bearing.

237. "Investigates Air as Bearing Lubricant," Soc Auto Eng. Jour., Vol. 61, No. 11, Nov. 1953, p. 108.

Short abstract of paper by D. McKinley on Kingsbury thrust bearing.

238. JAY, D. J., "Levapads for High Speed Tracks," Fourth Annual Supersonic Track Symposium, Sept. 1957, (Presented by Ford Motor Co.)

The article describes a proposed application of hydrostatic gas lubrication to the sliding pads of a supersonic test track. The term "levapad" is the name the author uses for the more familiar recess bearing; also called pad or pool bearing in the literature. (Additional information is contained in a technical paper by Jay and Peithman.)

239. JAY, D. J., and H. W. PEITHMAN, "An Analog Study of Levapad Stability." ASME Paper No. 58-A-287.

A set of non-linear differential equations was derived to describe the self-excited vibration of an early levapad type. These equations were solved on the department electronic analog computer. The theoretical solution which included a non-linear damping term in the equation of motion agreed favorably with the experimental results of the Levapad I type for the one set of conditions considered. The study demonstrated the manner in which the relationship of the various parameters produced a self-excited condition and indicated how a system might be designed to eliminate the vibration. (Auth)

240. JOHNSTON, T. J., "Frictionless Bearing for Electric Motors," U. S. Patent 816 330, issued 1906.

A rather elementary form of bearing is described in which jets of pressurized air impinge upon a flat surface supporting it

against gravity while permitting it to rotate. Pressure at the plate, and therefore load-carrying capacity, is a function of the separation distance. The proper distance is therefore automatically maintained.

241. JONES, E. M. "Rotary Air Bearing" U. S. Patent 2,868,593, Jan. 13, 1959, 3 p.

This invention claims to consist of an improved air bearing in which a flat parallel-surface air bearing is combined with a spherical-surface air bearing. The spherical surface, in addition to providing a portion of the bearing lifting force, acts to position the flat parallel surfaces transversely to the direction of their main lifting action.

The stator and rotor of the air bearing are described. Advantages of the invention are specified.

242. JUNG, K., "Bearing for Accurately Running Shafts Using Ball Bearings," U. S. Patent 1 893 995, issued 1933.

The play in ball bearings may be taken up or adjusted by axially moving one of the ball races. The inventor substitutes an externally pressurized gas bearing for the mechanical devices normally used to effect the movement.

243. JUNGGREN, O., "Combined Thrust and Guide Bearing," U. S. Patent 947 392, issued 1910.

A description is given of an externally pressurized bearing system which can use steam as the lubricant.

244. KAESTLE, A., "Skiing on Air," Popular Science, June 1959, p. 240..

Compressed air jetted from small containers provides a cushion between skis and snow, lessening friction and increasing the speed of the run. (Auth)

No other information is available.

245. KATTO, Y., N. SODA, "Theory of Lubrication by Compressible Fluid with Special Reference to Air Bearings," 1952 Proc. Second Japanese National Congress on Applied Mechanics, National Committee for Theoretical and Applied Mechanics, May 1953, pp. 267-270.

By considering the pressure in a bearing to be a continuous and periodic function with period equal to $2\pi$ and the total mass

of air contained in the bearing clearance to be constant, these authors were able to mathematically manipulate the equation

$$\frac{dp}{dx} = \frac{6\eta U}{h^3}\left(h - \frac{k}{p}\right)$$

and arrive at a form of solution.

Conversions were then made to dimensionless forms and the results plotted. From their curves, one can find the position of the journal center (and also the friction coefficient), given the mean load and the velocity of the journal. The pressure distribution in the bearing can be found by making substitutions in the appropriate equation.

This appears to be a logical method of attack. However, the authors present no experimettal verification of their theory.

246. KEMP, J. F., "Centrifugal Manometer," ASME Paper No. 58-A-111

The operating principles and mechanical construction of a micromanometer which utilizes air in lieu of a liquid as working fluid, are described. Some of the noteworthy features of the instrument include its high sensitivity and accuracy, quick response, wide range, and ease of manipulation. Differential pressures of the order of $5 \times 10^{-3}$mm water gage can be measured with an error of 1 per cent under normal laboratory conditions. The maximum range of the prototype described is 25mm water gage, and the corresponding error at this value amounts to about 0.25 per cent. (Auth)

247. KETTLEBOROUGH, C. F. "Density Variation Effects in Stepped-Thrust Bearings." Trans. ASME-J Appl. Mech. Vol. 81, Series E, Sept. 1959, pp 337-340.

A stepped thrust bearing is considered. Normally the continuity relationship of constant volume is assumed but in this case the author has introduced the more general relationship of mass continuity thus permitting consideration of the variation of density. Thus both density variation and influence of stepped discontinuity have been investigated as they affect load-carrying capacity and coefficient of friction. Theoretical curves are shown, illustrating the importance of density on the operation of this type of bearing.

248. KINGSBURY, A. "Experiments with an Air Lubricated Journal," Journal American Society Naval Engineering, Vol. IX, 1897, pp. 267-292. Also Journal Worchester Poly Inst., Mar. 1900

(Not readily available and probably abstracted only)

In one of the first carefully controlled and reported experiments of this type, Professor Kingsbury measured point of nearest approach (and attitude) of journal and bearing, friction, and pressure distribution as functions of speed and load. He also noted the points at which wear took place. One of the conclusions drawn is the necessity of clearances between shaft and bearing in order for them to operate. Suggestions are also made on where best to introduce the lubricant. These suggestions are based on the existence of negative pressures in the bearing.

One of the famous contributors to the subject of bearings, Professor Kingsbury by this paper stimulated considerable interest in gas-lubricated bearings. His knowledge of the practical side of engineering is evidenced in the design of his test rig and instrumentation. The results which were only in fair quantititive agreement with the work of Towers and Reynolds were later explained by Harrison who considered the compressibility of the gas.

249. KIRKPATRICK, J. G., "Hydraulic Thrust Bearing," U. S. Patent 2 523 310, issued 1950.

This invention has for its primary object the provision of a thrust bearing for rotating shafts wherein the bearing will be free floating and wherein metal to metal contact upon the thrust surfaces of the bearing is prevented by the interposition of a fluid medium under pressure. (Auth)

The inventor states that gaseous lubricants may be used.

250. KLAHN, E., "Apparatus for Minimizing Friction and Vibration of Rotor Elements." U. S. Patent Re 20305 (Original No. 2 054 055), issued 1937.

The device described is peculiarly adapted for accomplishing the practically perfect balancing of rotors such, for example, as propellors, fly wheels, shafts, armatures, gyroscopes, turbine rotors, etc., as well as scale arms and the like. (Auth)

Externally pressurized air is supplied to a stationary shaft which has a longitudinal pocket cut into it. The practically frictionless support enables the movable member to be prefisely balanced. The use of additional pockets is suggested to trap the air and thus provide a cushion against vibrations. Provisions are also made to cause rotative motion of the part to be balanced.

251. KLAHN, E., "Art of Sustaining Bodies in Space," U. S. Patent 1 629 577, issued 1927.

In a gyroscope: a rotatable support member having an upper bowl position; and a free, spherical member adapted to rest and to rotate therein and solely air supported during rotation. (Official Gazette)

252. KLASS, P. J., "Ceramic Gyroscope Uses Gas Bearings." Aviation Week, June 6, 1960, pp. 81-85.

News item on a miniature integrating gyro that uses a spinning rotor made of ceramic, supported in gas bearings. It has been developed by Minneapolis-Honeywell's Aeronautical Division.

The new gyro measures 2.8/2.75 in. and weighs slightly less than 0.7 lbs.

The gas bearing offers a nearly frictionless support and without the spurious torques that can result in conventional bearings. With gas bearing, the spinning rotor is supported on a thin film of gas, such as helium or air, which measures 25 millionths of an inch in thickness.

253. KOCHI, K. C., "Characteristics of a Self-Lubricated Stepped Thrust Pad of Infinite Width with Compressible Lubricant," Journal of Basic Engineering, Trans. ASME, Vol. 81, Series D, No. 2, June 1959, pp. 135-146. ASME Paper No. 58-A-1941.

Harrison's equation for the pressure in a gas-lubricated bearing of infinite width is solved for a thrust pad with stepped configuration. Analytic expressions for the pressure and load are developed. Numerical results are presented graphically. The analytic expressions together with the numerical data permit most of those characteristics of the stepped pad of practical interest to be comlletely determinable. Determination of optimum design parameters is given by a pair of graphs. (Auth)

254. KOENDERS, M. A., "A Survey of Hydrodynamic and Hydrostatic Lubricated Bearings," APEX 390, OTS, US Dept. of Commerce, Wash., D. C.

A search of the unclassified literature and General Electric reports has been made with reference to the use of air as the lubricating fluid in hydrostatic and hydrodynamic bearing applications. (Auth)

This publication is in essence the state of the art as the author found it. Being rather concise (25 pages) it serves to familiarize the newcomer to the field with what has been done. All applicable references from this work have been included in this bibliography.

255. KOTLIAR, I. M. "K Teorii Vozdushnykh Podvesov Sfericheskogo Tipa" (On the Theory of Air-Lubricated Spherical Bearings) Izvestiia AN SSSR, Otdel, Tekh. Nauk, Mekh. Mashinostr. No. 6, Nov.-Dec. 1959, pp. 21-26.

The author presents comparative data on the determination of pressures in actual and theoretical bearings. As an example, pressures were calculated for the case of vertical displacement of a ball floating in a spherical bearing with one, symmetrically located, inlet hole. An isothermal flow was assumed. The results of this case were compared with the solution of the exact case. The real clearance distribution was approximated by one which would allow the transformation of Reynolds' equation into Laplace's equation. Formulae are given for the solution of arbitrary cases.

256. KOTLIAR, Ia. M. "On One Possibility of Obtaining an Exact Integral of Reynolds Equation in Closed Form" Soviet Phys.-Doklady, Vol. 4, No. 4, Feb. 1960. pp. 761-764. (Translation of Doklady A. N. SSSR, Vol. 127, No. 1, July/Aug. 1959, pp. 59-62)

A solution to one form of Reynolds' equation for hydrodynamic lubrication was obtained. Conditions imposed were the use of a narrow opening with fixed walls using slow steady flow and constant kinematic viscosity. By the use of the stream function and an approximation for the film thickness, the solution to the equation for pressure is reduced to the solution of Laplace's equation. Boundary conditions are imposed and an equation for flow is derived.

257. KOWASKI, Y., "Seimitsukiakai (On the Air-Lubricated Bearings)," Journal Society Precision Machinery of Japan, Vol. 13, No. 5, 6, 7, pp. 39-44, No. 152, 153, 154, May-July 1947.

An analysis based on Reynolds' theory is given for an air-lubricated spherical bearing. The results of the analysis are then extended to the case in which the moving part of the bearing takes the form of a circular disk. The theoretical work is supplemented with experimental results.

258. KREITH, F., R. EISENSTADT, "Pressure Drop and Flow Characteristics of Short Capillary Tubes at Low Reynolds Numbers," Trans. ASME, Vol. 79, No. 5, July 1957, pp. 1070-1078.

The pressure drop and flow characteristics of short capillary tubes have been investigated experimentally for length-to-diameter ratios varying from 0.45 to 18 at diameter Reynolds numbers ranging from 8 to 1500. In the range of the dimensionless modulus $(L\mu)/(VD^2\rho)$ from $4 \times 10^{-3}$ to $3 \times 10^{-1}$, the experimental data agree within 15 per cent with a mathematical theory by Langhaar. At a value of $(L\mu)/(VD^2\rho)$ of about 0.3 the experimental data approach the Poiseuille laminar-flow theory (2). For very short

tubes ($L/D < 0.5$) the experimental results deviate from Langhaar's theory at values of $L\mu/VD^2\rho$ less than $4 \times 10^{-3}$, and at $L\mu/VD^2\rho$ equal to $5 \times 10^{-4}$, the pressure drop is twice as large as that predicted by Langhaar's theory. The experimental results for tubes having very short aspect ratios are in agreement with data obtained by Zucrow with short square-edged jets. It was found that the flow rate Q through a short capillary tube can be related empirically to the over-all pressure drop $\Delta p$ raised to a power N. The exponent N is a function of the length-to-diameter ratio L/D varying from 0.5 at L/D equal to 0.45 to 0.91 at L/D of 18. The trend of the curve suggests an asymptotic approach to unity, the exponent for Poiseuille-type flow. The results of this study have application to: (a) Simulating flow through screens, doors, cracks, and fissures in small-scale model testing of buildings in atmospheric wind tunnels. (b) Automatic control devices where capillary tubes are used as hydraulic resistances in a larger line and in nozzle-flapper combinations. (c) Heat pumps and air-conditioning equipment where short capillary tubes are used as two-way control valves. (d) Flow through compact heat exchangers and porous materials. (Auth)

This paper does not deal with gas bearings as such. However, the use of short capillary tubes occurs quite frequently and therefore, this paper could prove of value to persons engaged in gas bearing work.

259. LANGLOIS, W. D. "Isothermal Squeeze Films" IBM Res. Labs. San Jose, No. RJ-192, May 22,1961, 44 p.

A derivation is presented of the equation governing the pressure in a thin, flat film of ideal gas under isothermal conditions, when the surfaces bounding the film are in relative normal and tangential motion. When tangential motion is absent, the pressure equation reduces to a nonlinear heat equation, which admits of very few closed-form solutions. Various approximation methods are discussed, and two problems involving small periodic variation of the gap between parallel plates are solved by perturbation methods for a film in which fluid inertia is negligible. (Auth)

260. LAUB, J. H. "Evaluation of Externally-Pressurized Gas Pivot Bearings for Instruments." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 435-481.

Orifice-regulated hydrostatic gas bearings offer significant advantages for instrument applications. In particular, gimbal bearings for inertial guidance systems can be designed with negligible starting torque and high stiffness, and for operation at extreme temperatures.

A literature search revealed the lack of convenient and accurate data for the design of hydrostatic gas bearings of various configurations, taking into consideration the effects of compressibility, which cannot be neglected at higher pressures.

Based on the Navier-Stokes equation, expressions for the significant parameters, i.e., pressure profile, gas-flow rate, gap height and load-carrying capacity of pad, step and journal bearings, are developed. These parameters yield results which are in excellent agreement with experimental data. The test fixture incorporates pneumatic loading by means of a bellows-suspended piston which is prevented from cocking by an air bearing.

261. LAUB, J. H. "Gas-Lubricated Bearings" JPL Pasadena, Calif. Tech. Release No. 34-33, March 22, 1960, 4 p.

Because of the low viscosity of gases, the load-carrying capacity of hydrodynamic gas bearings is limited to about 0.5 to 1.0 psi of projected bearing area when the bearing has to start under load and to about 10 psi when the load can be applied after the shaft has reached speed. Hydrostatic gas bearings have practically unlimited load-carrying capacity even at low or zero speed but require an external supply of pressurized gas or vapor. Speeds of 60,000 rpm and higher have been reported for strictly hydrodynamic gas bearings and up to 250,000 rpm for such bearings with hydrostatic assist in starting. A viscous flow theory was developed which correlates well with experimental results on pad, journal, and spherical bearings.

262. LAUB, J. H. "Hydrostatic Gas Bearings"
ASME Trans.-J Basic Engng. 1, Vol. 82, Series D, No. 2, June 1960, pp. 276-286.

Orifice-regulated hydrostatic gas bearings offer significant advantages for instrument applications. In particular, gimbal bearings for inertial guidance systems can be designed with negligible starting torque and high stiffness, and for operation at extreme temperatures.

A literature search revealed the lack of convenient and accurate data for the design of hydrostatic gas bearings of various configurations, taking into consideration the effects of compressibility. Compressibility cannot be neglected at higher pressures.

Based on Euler's equation, expressions for the significant parameters, i.e., pressure profile, gas-flow rate, gap height, and load-carrying capacity of pad and step bearings, are developed. These parameters yield results which are in excellent agreement with experimental data. The test fixture incorporates pneumatic loading by means of a bellows-suspended piston which is prevented from cocking by an air bearing. (Auth)

263. LAUB, J. H. "Externally Pressurized Journal Gas Bearings" Trans. ASLE, Vol. 4, No. 1, April 1961, pp. 156-171

Externally pressurized gas-lubricated bearings with multiple orifice feeds are investigated. An analytical treatment is developed for a semicylindrical bearing with 9 orifices and for a cylindrical journal bearing with 192 radial and 24 axial orifices..

Experiments are described on models of the two bearing configurations with specially designed fixtures which incorporate pneumatic loading and means for determining pressure profiles, gas flow, and gap height. The correlation between theory and experiment is satisfactory. (Auth)

264. LAUB, J. H. "Dual-Sphere Gas-Floated Gyro" JPL Research Summary, No. 36-9, Vol. 1, April-June 1961, pp. 22-23 .

The author gives a brief presentation of the concept and potential of the dual-sphere gas-floated gyro. In a schematic form, it is shown that two concentric masses of spherical configuration are separated by a thin film of compressed gas. This film supports the inner rotor. The outer rotor is supported by gas bearings, which may be of the hydrodynamic type, or hydrostatic type. The outer rotor is driven either by an electric motor or mechanically by turbine action of gas jets. The gyro is spun up with the inner rotor caged mechanically. When operational speed is reached, the inner mass is uncaged and continues to spin at the same speed and around the same axis as the outer rotor. It is claimed that this virtually eliminates any viscous drag as well as wear, by metal-to-metal friction. The angular motion of the outer rotor with respect to the inner inertial reference is read out optically, or by electrical pickups.

Advantages of this system over conventional gyros are claimed: (a) increased life expectancy due to the absence of metal-to-metal contact of rotating surfaces (b) increased load-carrying capacity which is limited only by the available gas pressure; (c) high-g capability and stiffness can be obtained with moderate pressure; (d) in low-g environments, the pressure can be still further reduced with attendant savings in power; (e) elimination or substantial reduction of the effects of mass shifts due to anisoelasticity; (f) great reduction of temperature effects due to motor losses since the rotor is effectively thermally isolated.

265. LAUB, J. H. and H. D. McGINNES "A Closed-Cycle System for Gas Bearings" JPL Pasadena, Calif., Tech. Release No. 34-174, Jan. 19, 1961, 17 p.

The support of sensing masses of inertial instruments by gas lubrication and flotation has considerable advantages. However,

in missions of long durations, such as lunar or planetary explorations, the storage of expendable gas becomes impractical because of the size and weight of the container. A closed-cycle system in which the gas is recirculated becomes mandatory. Consideration was given to the feasibility and performance of a thermally pumped closed-cycle vapor system for gas-lubricated bearings and gas-floated inertial instruments in space vehicles. The study indicated that a closed-cycle system using Freon or some other fluid with similar thermodynamic properties is feasible for spacecraft applications. The thermal pumping power can be obtained directly from solar radiation (in panels or concentrators) or from nuclear reactors. Condensation of the fluid is accomplished by exposing it to the dark side of the craft. The liquid is returned to the evaporator by a miniature mechanical pump or by capillary action. The pumping power for small liquid flowrates is considered negligible. (Author)

266. LAUB, J. H. and H. D. McGINESS "Gas-Floated Spinning Spheres" JPL Pasadena, Calif. Tech. Rept. No. 32-61, Feb. 28, 1961, 8 p.

Spinning masses of spherical configuration, supported by compressed gas, offer considerable interest to inertial guidance and control techniques. Typical applications involve stable gyro references and momentum-transfer devices for spacecraft-attitude control. The viscous drag and power requirement of gas-floated spheres spinning within a concentric hollow shell and within a multiple-pad system are analyzed as functions of rotational velocity, sphere diameter, spin-axis direction, and gas characteristics. (Author)

267. LAUB, J. H. and R. H. NORTON, Jr. "Externally Pressurized Spherical Gas Bearings" Trans. ASLE, Vol. 4, No. 1, April 1961, pp. 172-180

Spherical gas-lubricated bearings are of considerable interest in applications, requiring a pivoting or rotating support with three degrees of freedom. This would be of value for instance in attitude control simulators of space vehicles. An analytical and experimental study of externally pressurized spherical gas bearings with orifice regulation is presented along with the experimental findings. These are in good agreement with the predictions of viscous flow theory. (Auth)

268. LEARY, W. M., D. H. TSAI, "The Measurement of Air Flow by Means of the ASNE Square-Edged Orifice with Flange Taps," Sloan Laboratory, MIT, Cambridge, Mass., 1950.

The work by these authors is included as part of a collection of contributions by various persons to a volume entitled "Aerodynamic Measurements" by Robert C. Dean, Jr. Both Leary and Tsai have written on flow metering. The reference is cited as one of the possible sources for obtaining information on flow measurements and flow measuring devices.

269. LICHT, L. "Axial, Relative Motion of a Circular Step Bearing" Franklin Inst. Labs. Res. Devel., Tech. Rept. No. I-A2049 Oct. 7, 1959; Trans. ASME-J Basic Engng. Vol. 81, series D, No. 2, June 1959, pp. 109-117, ASTIA No.AD-231065

Equations relating the flow of the lubricant and the axial motion of an externally-pressurized thrust bearing are developed. The bearing is shown to be stable when the fluid is incompressible.

Expressions for local stiffness and damping coefficients, useful in the evaluation of the dynamic response of the bearing are given.

An analog computer solution of the equation of motion is compared with the results of the corresponding, small displacement equation. (Author)

270. LICHT, L. "Stability of Externally Pressurized Gas Journal Bearings" Franklin Inst. Labs. for Research and Dev. Rept. No. I-A2049-8, Oct. 1959, 36 p./ also in Trans. ASME-J. Appl. Mech., Vol. 27, Series E, No. 2, June 1960, pp.250-258, ASTIA No. AD-228299.

A stability analysis is developed for gas journal bearings having externally pressurized pads, symmetrically spaced along the circumference. Simplifying assumptions are made and equations of flow and motion are stated in terms of perturbation quantities.. The case considered is when the journal, initially in an eccentric equilibrium position, begins to move in an arbitrary direction under the influence of a small, random disturbance. Methods of factorizing and simplifying the characteristic determinants are shown, with the objective of reducing the work of examining the roots of characterissic equations. Special cases, such as the bi-directional thrust bearing and that of the journal initially in concentric position are discussed. Numerical and semi-experimental procedures of determining the coefficients of characteristic equations are outlined. Stability tests are suggested. A simple numerical example is included. Bearing parameters affecting stability are discussed. (Author)

271. LICHT, L. "Extension of the Conducting Sheet Analogy to Externally Pressurized Gas Bearings", Franklin Inst. Labs. Res. Develop., Rept. No. I-A2049-9, Oct. 1959, 15 p. also Trans. ASME-J, Basic Engng., Vol. 83, Series D, No. 2, June 1961, pp. 209-212. ASTIA No. AD- 228-300.

Incompressible, viscous flow in narrow passages bounded by parallel surfaces yields the 2-dimensional Laplace equation $\nabla^2 P = 0$. The pressure field, load capacity and lubricant flow ofhhydrostatic oil bearings can be readily determined by means of the electric analogy of the conducting sheet. The equation

$$\frac{\delta}{\delta x}\left(P\,\frac{\delta P}{\delta x}\right) + \frac{\delta}{\delta y}\left(P\,\frac{\delta P}{\delta y}\right) = 0$$

characterizes laminar, isothermal flow of gas lubricants in otherwise geometically identical bearings. It is shown that by means of suitable change of the dependent variable the above equation can be reduced to the Eapacian form. The ensuing advantage is the extension of the conducting sheet analogy to externally pressurized thrust and journal guide bearings when the lubricant is a gas. (Author)

272. LICHT, L. and H. G. ELROD "An Analytical and Experimental Study of the Stability of Externally-Pressurized, Gas-Lubricated Thrust Bearings". Franklin Inst. Labs. Res. Devel., Tech. Rept. No. I-A2049-12, Feb. 1961, 209 p.

The subject of this investigation is the stability of externally-pressurized, gas-lubricated bearings. An analysis is made which treats the flow within the gas film on a distributed, rather than on a lumped parameter basis. Rectangular and circular bearing configurations are considered and the effect of several parameters on stability is investigated. Results of the present analysis are compared and contrasted with those obtained from earlier, simplified theories. The experimental program pursued here is guided by the analysis. An apparatus is designed, constructed and instrumented to provide for the variation of governing parameters and for the accurate determination of their critical values. Comparison of theory and experiment is made and the validity of theoretical assumptions, relative to the experimental model, is discussed. (Author)

273. LICHT, L., D. D. FULLER, "A Preliminary Investigation of an Air-Lubricated Hydrostatic Thrust Bearing," ASME Paper 54-LUB-18, 1954.

Because of the growing interest in the lubrication of bearings with air, this investigation of a simple hydrostatic thrust bearing was undertaken. Equations are developed for load-carrying, film thickness, pressure profile and volume of air required for a typical thrust bearing. Conditions leading to stability of operation are also considered. A comparison of theoretical and experimental values shows that within the limits of the test data the performance characteristics of this bearing can be predicted with good accuracy. (Auth).

The author offers a series of curves which, for his model, enable one to determine the flow and supply pressure required to carry a load at a specified film thickness. His note of bearing instability and its correction (by reducing the depth of the recess) is almost passed over. An analysis of this problem is promised in a subsequent paper.

274. LICHT, L., H. G. ELROD, "A Study of the Stability of Externally Pressurized Gas Bearings," The Franklin Institute - Laboratories Interim Report I-2049-4, Nov. 1958. Contract Nonr-2342(00) Task NR 097-343. AECU 3913, OTS. ASTIA No. AD-206762.

The subject of this paper is the stability of externally pressurized gas bearings.

The pertinent equations are linearized and the stability criteria stated in considering small deviations from the equilibrium point.

The flow in the bearing clearance is treated on a distributed rather than on a lumped parameter basis. Results thus obtained, when compared with those previously arrived at by means of a simplified analysis, show a marked divergence in the limitingg values of parameters which influence the stability of the bearing.

Differences in predictions to the simplified and present analyses with regard to the permissible compression volume in the bearing interspace and the effect of varying the mass of the bearing are emphasized and discussed. (Auth)

275. LICHT, L., D. D. FULLER, B. STERNLICHT, "Self-Excited Vibrations of an Air-Lubricated Thrust Bearings" Trans. ASME, Vol 80, No. 2, Feb. 1958, pp 411-414.

The authors attack the problem of instability in air-lubricated bearings and relate it to the air storage capacity. In a straight forward mathematical treatment backed up by experimental data they show, for a disk-type externally-pressurized air bearing with a centrally located recess, the most stable conditions occur with small recess depths (small air storage capacity), high recess pressures and minimum bearing clearances. In the course of the work they find the use of large nozzles is preferred to small ones and nozzles in general are preferred to capillaries. The work also shows that a choked condition at the nozzle leads to instability.

276. LIEPMANN, H. W., "Gaskinetics and Gasdynamics of Orifice Flow" J. Fluid Mechanics, Vol. 10, Part I, Feb. 1961, pp. 65-79.

The paper gives the result of a study on the efflux of gases through circular apertures. The problem is considered as an example of a transition from the gas-dynamic to the gaskinetic regime.

The mass flow of helium, argon and nitrogen was measured for a range of upstream pressures corresponding to (mean free path)/(aperture diameter) from about 50 to 5 x $10^{-3}$; within this range the transition from molecular effusion to inviscid, transonic flow takes place. The theory for the two asymptotic limits is discussed and first-order corrections to the free molecular and inviscid limit formulae are given. (Auth)

277. LINDHARDT, P., "The Hydrostatic Gas-Bearings as a Non-Touching Gland for Rotating Shafts" British Hydromechanics Research Assoc., Intern. Conf. on Fluid Sealing, Paper C2, April 1961, 8 p.

The possibility of maintaining a uniform gap between the sealing faces of a radial face seal by the introduction of a series of pressurized pockets in the stationary face is examined. Expressions giving the gap thickness and the condition for high axial stiffness in terms of the sealed pressure and seal geometry are derived. Preliminary experimental results have shown that the seal is capable of operating satisfactorily. (Auth)

278. LOCH, E., "Untersuchungen an Gaslagern" (Research on Gas Bearing) Escher-Wyss, Nachrichten, 1960, pp. 118-124.

This is a report of "Escher Wyss", Ltd., Switzerland, on research on aerodynamic and aerostatic bearings.

It states that gas-lubricated bearings have been used successfully in the atomic, chemical and refrigeration industries. In aerodynamic bearings, the load-carrying capacity is low because of the low viscosity of the lubricant gas. More heat is dissipated in gas-lubricated bearings; therefore the temperature of the gas film is lower than that of the oil film. Gas bearings are mostly used for rotating blowers in atomic installations; the gas being circulated is the lubricant. At high speeds, a special construction of the bearings (as pocket-like cavities) can prevent a vortex of the gas film and instability of operation.

Aerostatic bearings (externally-pressurized) are most suitable for heavy, slow-moving engines. Whereas constant use of pressurized gas seems to make this system uneconomical, this is compensated by the lower friction above a certain speed. A compromise has to be made between the load-carrying capacity and gas consumption. This action is improved if the nozzles open into a widened chamber of ringlike channel. By the use of special "LAVAL" nozzles (patented by ESCHER-WYSS) pressure can be increased

at the same cross-section over the pressure permissible at cylindric nozzles. Vibrations on account of pressure differential are dampened by installation of Helmholtz-resonance chambers, which work like sound dampeners at different frequencies. An experimental device for studying fast moving shafts (up to 20,000 rpm) on fixed gas bearings was installed. The lower damping capacity of the gas causes a steeper increase in amplitude close to the critical speed of rotation.

279. MACKS, E. F., "Lubrication Reference Manual for Missile and Space Vehicle Propulsion at Temperatures about 700° F." Wright Air. Devl. Center, Tech. Report 58-638, Vol. 1, Part I, Jan. 1959, 468 p., AD-213 474.

This report is an extensive survey, study and analysis of high temperature (above 700 F) lubrication, friction and wear requirements and problems relating to primary and secondary propulsion systems of missiles, satellites and space vehicles. The report covers work conducted from June 1958 to January 1959.

Air, pure gases, clean decomposition gases of monopropellants or clean combustion gases of bipropellants are discussed as unique lubricants used in pneumodynamic (self-acting) and pneumostatic (externally-pressurized) bearings. The high temperature capabilities of air and other gases are acknowledged. "Protective atmosphere" lubrication and vapors as lubricants are reviewed in the light of experimental results and the literature.

280. MACKS, E. F., "Gas Lubrication of Bearings at veryHigh Temperature" Tribo-Netics Labs., Vermilion, Ohio, Contract No. AF 33 (616) 5982, Report. No. 2, March 15-June 15, 1959, 29 p.

The objectives of this program were to design and operate a high-speed gas bearing in an inert ambient atmosphere at temperatures from 80 F, up to 1500 F, or higher. An inert-gas lubricating system and a gas-bearing test rig were designed and evaluated for operation up to 1800 F.

From three methods considered for supplying inert gas to the rig, bottled gaseous nitrogen having minimum purity of 99.9% was selected. A bank of 12 cylinders having a capacity of approximately 3300 ft. was used. For secondary power applications the gas can be supplied by a separate gas generator system or by bleed-off from the reaction chamber. Calculations are given showing that a separate gas generator for a maximum rate of 3 lb/hr is impractical. With a "bleed-off" system for a representative 40 horsepower hot-gas turbine the additional propellent weight flow requirement to lubricate the turbine gas bearing amounts to less than 1%. Pressure regulation, filters and time delay for the "bleed-off" system are considered.

Three different test rigs designs have been considered and advantages and disadvantages of each are discussed. The design selected consists of a gas-bearing mounted in a furnace in cantilever fashion supported by two bearings outside the furnace. Air was used to drive an impulse turbine that drives the test bearing shaft. Instrumentation measured torque, load, speed and temperature gradients.

Three basic test bearing types (a) axial and circumferential orifice-pad compensated, (b) modified step, and (c) high-ambient-pressure pneumodynamic (self-acting) were designed with four different room-temperature clearance values. Tentative conclusions were that Inconel X or an alloy of molybdenum as base materials would be used on either the rotating or stationary member, since only inert gases would be utilized in this program. If an oxidizing environment were to be present, high density alumina or suitably coated Inconel X or molybdenum alloy would be considered as bearing materials. (Author)

281. MACKS, E. F., "Gas Lubrication of Bearings at Very High Temperature" Tribo-Netics Labs Wright Air Development Centre Report 59-783, Contract No. AF 33(616)-5982, Jan. 1960, 117 p; ASTIA No. AD-237 394.

The objectives of this program are to advance the "state-of-the-art" of very-high-temperature gas lubrication of high-speed bearings and to design and fabricate a gas-lubricating system, a test rig and experimental gas bearings to operate at high speed in an inert atmosphere at temperatures from 80 F up to 1500 F or higher.

An inert-gas lubricating system, a gas-bearing test rig and gas bearings have been designed and fabricated. Static calibration tests have been conducted over the temperature range 80 to 1500 F.

The lubricating system was chosen from several possibilities and consists of supplying gaseous nitrogen from bottles through a stainless steel network including valves, flow meters, pressure regulators, filters and heaters so as to introduce a controllable flow of clean gaseous nitrogen to the test bearigg. Provisions for cleanliness during assembly and operation have been made. For secondary power applications the gas can be supplied by a separate gas generator system or by bleed-off from the reaction chamber. Calculations are given showing that a separate gas generator for a maximum rate of 3 lb/hr is impractical. With a "bleed-off" system from a hot-gas turbine for a representative secondary power system, the additional propellent weight flow requirement to lubricate the turbine gas bearing amounts to less than 1%. Pressure regulation, filters and time delay for the bleed-off system are considered.

The test-rig design consists of a gas-bearing mounted in a furnace in cantilever fashion supported by two bearings outside the furnace. Air is used to drive an impulse turbine that drives the test bearing shaft. Instrumentation to measure torque, load,

speed and temperature gradients is provided. Electrical resistance heaters and furnaces provide clean, uniform heat to the test components and gaseous lubricant.

The special test shafts are provided with both liquid and air cooling of the front support spindle bearing. The shafts are hollow to permit uniform temperature gradients at the test bearing and to permit the entrance of cooling air from the turbine end. The shafts are made from Inconel X to rigid specifications including aluminum oxide flame plate over the entire test bearing area (final radial thickness of flame plate is 0.003 in.) The test shaft is supported on a size 203 deep groove ball bearing at the tubbine end and a 1-1/2 in. diameter x 3/4 in. length hydrodynamic bearing (with a circumferential groove and pressure pad) at the test bearing end in order to provide required shaft stiffness.

Three basic test bearing types were chosen from many considered as being best suitable for high-temperature evaluation. These types are: (a) fully-choked, orifice-compensated pneumostatic bearing of special design, (b) modified-step pneumostatic bearing, and (c) high ambient pressure pneumodynamic bearing. Analyses of the bearings were made to establish rational design criteria for very high-temperature operation. It was determined that widely different design considerations are applicable to gas-bearings which must operate over a wide temperature range, and in addition under a wide range of speeds and loads, as compared to gas bearings designed for a specific operating condition at room temperature. The test bearings were fabricated from Inconel X so as to have the same coefficient as the test shaft. In an oxidizing atmosphere-high-density alumina is a promising material choice for both journal and bearing.

A technique which offered reasonable promise for accurate and meaningful bearing clearance and bearing eccentricity measurements for the operating conditions of this program was evaluated. A gas gaging technique with four nozzles at 90 degrees at each end of the test bearing was employed. By means of precision flow meters and careful static calibration, (with a test bearing and test shaft) over a temperature range 80 F to 1500 F it was determined that the results are erratic and that temperature correction factors are too large to be meaningful for the precision required. An alternate method of determining clearance and eccentricity by means of theoretical expressions and accurate lube-flow, temperature and pressure meansurements is discussed. (Author)

282. MACKS, E. F., "Gas Lubrication of Bearings at very High Temperatures and Low Flow Rates" Tribo-Netics Laboratories Quarterly Progress Report, No. 1, Jan. 15 - April 15, 1960 USAF Contract No. AF 33(616)-6917. 43 p.

A prime objective of this program is to design and operate a high-speed gas bearing in an inert ambient atmosphere at temperatures from 80 F up to 1500 F. or higher at low flow rates. An inert-gas lubricating system and a gas bearing test rig designed for operating temperatures up to 1800° F are being used for the evaluation.

A pneumostatic bearing, 1.500 inch diameter with a normal diametral clearance of 0.00125 in. has been run successfully at numerous equilibrium test conditions which encompass a temperature range from 80 F to 1500 F with nitrogen lubricant flow rates from approximately 3 to 34 lbs/hr at speeds to 20,000 rpm.

A comparison of theoretical and experimental results indicates correlation was excellent under certain operating conditions but that appreciable deviations existed for other operating conditions. Known correction factors do not fully explain the deviations between theoretical and experimental results. (Author)

283. MACKS, E. F., "Gas Lubrication of Bearings at very High Temperatures and Low Flow Rates" Tribo-Netics Laboratories, Quarterly Progress Report No. 2, April 15 - July 15, 1960, Contract No. AF 33 (616)-6917, 55 p.

A prime objective of this program is to design and operate a high-speed gas bearing in an inert ambient atmosphere at temperatures from 80 F up to 1500 F or higher at low flow rates. An inert gas-lubricating system and a gas-bearing radial-load test rig designed for operating temperatures up to 1800 F are being used for the evaluation.

Pneumostatic bearings of 1.5000 inch diameter with nominal diametral clearances from 0.0006 in. to 0.0010 in. have been evaluated at numerous equilibrium test conditions which encompass a temperature range from 80 F to 1500 F with nitrogen lubricant flow rates from approximately 1.3 to 29 lbs./hr. Preliminary flow orientation studies at room temperatures have been conducted at speeds to 64,000 rpm (equivalent DN 2.44 x $10^6$).

Simplified studies of numerous potential materials have led to a better material combination for high-temperature gas bearings than has previously been employed. Flame Plated LA-2 over Inconel X as the shaft member versus Flame Plated LW-5 over Inconel X in the bearing bore is superior to other combinations investigated to date.

A novel design concept has been developed for Type I pneumostatic bearings (orifice compensated) which utilizes temperature compensated annular orifices (TCAO). Theoretical studies indicate that the TCAO bearing design will allow close to optimum load capacity performance over a very wide temperature range whereas fixed orifice bearings are designed for specific operating conditions with load capacity characteristics deteriorating rapidly at other than the design tempertture.

284. MACKS, E. F., "Gas Lubrication of Radial and Thrust Loaded Bearings at Very High Temperatures and Low Flow Rates" Tribo-Netics Laboratories Quarterly Progress Report No. 3 - July 15 - Oct. 15,1960, Contract No. AF 33(616) - 6917, 56 p.

The prime objectives of this program have been extended to include thrust as well as journal pneumodynamic and pneumostatic bearings and means of evaluating the lubricant-bearing systems (Rig B) in an inert atmosphere at temperatures from 80 F or higher at low lubricant flow rates. Specific requirements are given in the report.

Room temperature and high-temperature prototypes of Test Rig B have been built and evaluated. Test Rig B allows evaluation of both thrust or journal bearings of the pneumodynamic and pneumostatic types. Completely revised lubrication and instrumentation systems allow evaluation of both thrust and journal bearing lubricant systems.

Flow orientation studies have been conducted on the room temperature prototype of Rig B to speeds of 64,000 rpm (DN equivalent value 2.44 million). The high temperature prototype of Rig B has been operated to speeds of 40,000 rpm at 1000 F. The final high temperature design of Rig B is completed and is being fabricated. Preliminary results of high-speed, room-temperature and high-temperature tests are given.

Theoretical analyses result in generalized flow data for Type I orifice-compensated bearing which serves as a guide for experimental studies. Analyses of experimental data lead to an explanation of lubricant flow deviations between theoretical and experimental results at room and high temperatures. A comparison of the Tribo-Netics approximate analysis and the Boeing analysis for Type II pneumostatic step bearing is presented. (Auth)

285. MACKS, E. F., "Gas Lubrication of Radial and Thrust Bearings at Very High Temperatures, High Speeds and Low Lubricant Flow Rates" Tribo-Netics Laboratories, Second Summary Report. Wadd Technical Report 61-83. Contract No. AF 33 (616)-6917, Feb. 1961, 157 p.

Nitrogen-lubricated radial bearings, 1.5000 inch diameter with nominal diametral clearances from 0.0006 inch to 0.0018 inch have been evaluated at numerous equilibrium test conditions which encompass a temperature range from 80 F to 1500 F with lubricant mass-flow-rates from approximately 1.3 to 40 lb/hr under radial loads to 20 pounds.

Nitrogen lubricated radial and thrust bearings have been operated successfully from 80 F to 1500 F over the entire speed range zero to 65,000 rpm under small combined radial and thrust loads.

Flow orientation studies at room temperature under radial load have been conducted at speeds to 78,660 rpm (equivalent DN $3.0 \times 10^6$).

Lubricant flow calibration tests have been made with thrust bearings using gaseous lubricants of Air, He, A and $CF_4$ with $N_2$ as a reference lubricant for loads to 100 lb and mass flow rates from 0.19 to 2.23 lb/hr.

Theoretical expressions have been derived for several types of radial and thrust gas bearings relating lubricant mass flow rate, load capacity, lubricant film thickness and bearing stiffness (in certain cases) as a function of gas lubricant viscosity and operating temperatures to 2000 F.

A comparison of theoretical with experimental results indicates correlation to be excellent under certain operating conditions but that appreciable deviations existed for other conditions. Known correction factors do not fully explain the deviations between theoretical and experimental results in all cases. (Author)

286. MACKS, E. F., "Gas Lubrication of Bearings at Very High Temperatures, High Speeds and Low Lubricant Flow Rates" Tribo-Netics Laboratories, Progress Report No. 1, Feb. 15, 1961 - June 15, 1961; Contract No. AF 33 (616) 8047; 64 p.

Dynamic room and high-temperature thrust and combined-load stability studies have been conducted in Test Rig B over the temperature range 80 F to 1500 F.

The critical components of an all-ceramic Test Rig C have been designed, manufactured and successfully operated over the entire speed range 0 to 65,000 rpm (DN equivalent 2.5 million) at 1500 F.

Lubricant flow studies and preliminary dynamic tests with thrust bearings have been conducted in Test Rig B at temperatures over the entire range from 80 F to 1500 F using gaseous lubricants of He, A and $CF_4$ with $N_2$ as a reference lubricant.

It has been determined experimentally that mass flow rates of the various gaseous lubricants studied under essentially identical operating conditions over the temperature range 80 F to 1500 F are dependent not only upon the viscosity and density effects of the lubricant per se, but also upon the interrelated effects of these and other lubricant properties as affects gas-lubricating-film thickness.

Theoretical expressions have been derived and are being generalized for two types of thrust gas bearings relating lubricant mass flow rate, load capacity, lubricant film thickness and bearing stiffness as a function of gas lubricant viscosity for operating temperatures from 80 F to 2000 F. The combined effects of rotational and pressure induced flow have been derived and preliminary results are given.

A comparison of theoretical with experimental results indicates correlation to be excellent under certain operating conditions but that appreciable deviations existed for other conditions. (Auth)

287. MANN, M., "Here Come Cars Without Wheels," Popular Science, July 1959, pp. 51-55, 194.

You'll ride low and fast on a bubble of compressed air, in fantastic new "sleds." They whoosh across fields, swamp, water-anywhere-at speeds that could match airplanes. (Auth)

The devices described do support themselves on a cushion of compressed air. Some "ride" only a fraction of an inch above the lower surface, others a few inches. ("Film thicknesses" of thirty feet or more are predicted by the people making these sleds.)

Classification of these sleds as gas bearings may be questioned. The reference is included here to note their existence.

288. MARCO, S. M., "Rotary Nozzles for Soot Blowers and the Like," U. S. Patent 2 752 197, issued 1956.

An object of this invention is to provide a rotary soot blower nozzle so designed that all lubricants that would be detrimentally affected by high temperatures are eliminated.

The invention aims to provide an improved nozzle (for a soot blower) which may be used within the high temperature regions of a water tube boiler without requiring lubricants for the relatively moving parts which are detrimentally affected by the high temperatures (2500°F) within the furnace. The construction is such that moving parts are floatingly mounted by the cleaning medium, commonly air, which is introduced between the bearings of the relatively moving parts during the cleaning operation, and the cleaning medium is also employed to rotate the nozzle on the lance tube. (Auth)

289. MAYER, J. E., Jr. "Controlled Externally Pressurized Bearings" Ph.D. Thesis, MIT, June 1960, 163 p.

(Paper not available for review as of July 1, 1961)

290. MICHAEL, W. A., "A Gas Film Lubrication Study, Part II; Numerical Solution of the Reynolds Equation for Finite Slider Bearings," IBM Journal of Research and Development, Vol. 3, No. 3, July 1959, pp. 256-259.

This paper presents a finite-difference technique for obtaining approximate numerical solutions to the Reynolds partial differential equation of gas film lubrication theory. A digital computer program is described, and discretization errors and stability of the difference equations is discussed. (Auth)

See W. A. Gross and R. K. Brunner for Part I and Part III of this group.

The three papers, Parts I, II and III taken together represent an idealized attack on a gas bearing research problem. The theoretical analysis, the numerical solutions and the experimental verification complementing each other admirably.

291. MICHELL, A. G. M., "Lubrication, Its Principles and Practices," Blackie, London, 1950, "Air Lubrication," pp. 168-169.

Contains a brief mention of the use of air as a lubricant.

292. MICHEL, R. O., "Pneumatic Bearing Construction," U.S. Patent 2 756 115, issued 1956.

Gas bearings are particularly designed to accommodate vertical and thrust loads normally encountered in the mass centering of a propellor blade. The device is essentially a cantilevered shaft supported by a force couple formed by two 180° bearings near one end. A number of orifices are used as the air inlet ports in the radial bearings and, in the necessary thrust bearings.

293. MICHELSON, H., "Bearings," U. S. Patent 2 738 238, issued 1956.

An externally pressurized fluid is used on a work-holding and positioning device to support a vertical load meanwhile permitting one of the members to rotate freely and accurately about the bearing center. This is accomplished by introducing the fluid inside the spaces formed by a series of interlocking annular grooves cut into the mating bearing plates.

294. MIROLIUBOV, I. V. and V. M. SHASHIN "Raschet Podderzhivaiushchei Sily Vozdushnogo Podshipnika Skol'zheniia pri Otsutstvii Vrashcheniia." (Caluulation of the Supporting Force of the Air Lubricated Slider Bearings in the Absence of Rotation) Izvestiia Vysshikh Ucheb. Zav. MVO SSSR, Seria Av. Tekh. No. 2, 1959, pp. 25-32

In this attempt to calculate the supporting force of the air lubricated slider bearing in the absence of rotation, the author considers the following parameters: (1) Axial flow, only; (2) bearing is divided in sectors (one per inlet hole); (3) enough inlet holes to consider constant gap throughout each sector; (4) the effect of curvature is neglected; (5) the inertia forces are neglected in comparison to pressure; (6) isothermal flow.

The solution is obtained by potential flow theory. The optimization of radial clearance for given geometrical factors and inlet pressures is obtained.

Results are given as curves of load carrying capacity against clearance, and of load carrying capacity against eccentricity ratio.

295. MIDWOOD, G. F., R. W. DUNCAN, "Tests on an Air Lubricated Thrust Bearing," Royal Aircraft Establishment Aero. Tech. Memorandum No. 5, Oct. 1947.

(Paper not available for review as of July 1, 1959.)

296. MÖLLER, W., "Bearing," U. S. Patent 2 068 458, issued 1937.

The flow of air to the bearings is automatically controlled by the relative motion of parts in a compass.

297. MONTANY, E. R., "An Analytical Study of the Load Carrying Capacity of a Journal Type Gas Bearing," Curtiss Wright, R-48-2, February 18, 1948, AF Contr. W33-038 ac - 14161, Project MX-772.

An analysis has been made of the load-carrying capacity of two types of journal gas bearings. Type 1 is a journal bearing with pressure inlet at the bottom and pressure outlet at the top. Type 2 has pressure inlets at both top and bottom and outlets at both sides. A series of charts is plotted which should prove useful in bearing design. (Auth)

The feasibility of the design of journal-type gas bearings by analytical means was investigated. The work resulted in a method of approach and a series of design chargs for two simplified externally-pressurized types of journal bearing.

The analysis is for one dimensional fluid flow of a compressible perfect gas in a bearing with small shaft displacement. End flow is neglected.

298. MONTGOMERY, A. G., F. STERRY, "A Simple Air Bearing Rotor for Very High Rotational Speeds," A.E.R.E. ED/R, 1671 (1956).

A high speed rotor (of 3/4" diameter) is capable of 250,000 r.p.m. driven by an air turbine; it runs on air-lubricated, externally supplied journal bearings, which consist of standard, sintered oil-retaining bronze bushes (with the oil extracted.) For purposes of sealing and flexibility, they are mounted on rubber 'O' rings. The thrust bearing is a single 0.020 inch diameter air jet in the middle of a flat surface. The rotor is a plain, ground cylindrical rod of tool steel with serrations milled at one end to provide a crude turbine wheel - it runs at a diametral clearance of about 0.003 inch. Bearing air consumption is about 10 c.f.m. The system could be made much smaller, both to achieve higher speeds and to economize in air consumption. (Auth)

The article itself is rather short yet quite important since the device permits attaining rather high rotational speeds. The use of the porous bronze bearing described is similar to the porous carbon graphite bearings patented by Becker.

299. MONTGOMERY, A. G., F. STERRY, TO UKAEA, "Gas Lubricated Bearings," Great Britain Patent 796 926, Nuclear Eng 4, 48, issued 1959.

When using gas lubricated bearings, instability of the rotor occurs under certain conditions, and may develop into violent back and forth movements of the rotor across the diameter of the bearing (as an oscillating piston in a double-ended cylinder.) An incipient oscillation is also present, determined by the mass of the rotor and the load/ displacement characteristic of the bearing. The clearance between rotor and bearing shell is of importance for this oscillation and, therefore, has to be kept extremely small (0.0005 in) and only very small tolerances are thus permissable. This clearance, however, can be raised to the order of 0.003 in for an 0.75 in rotor diameter by arranging the bearing sleeve to be surrounded by two rubber rings, one at each end which also act as gas seals in an annular chamber under gas pressure around the sleeve. (Nuclear Science Abstracts 13-8464.)

300. MORI, H. "A Theoretical Investigation of Pressure Depression in Externally Pressurized Gas-Lubricated Circular Thrust Bearings" Trans. ASME-J. Basic Engng. Vol. 83, Series D, No. 2, June 1961, pp. 201-208.

A theoretical explanation of the experimentally observed depression of the pressure profile in externally pressurized gas-lubricated circular thrust bearings is presented, based on a concept new to gas lubrication, that of the generation of a shock wave in the bearing clearance space. On the basis of an approximate mathematical model, the bearing pressure distribution and load capacity are determined, and the effects of several bearing parameters are discussed. Good qualitative agreement is found between the analytical results and available experimental data (Author)

301. "Motor Which Floats on Air," New York Journal of Commerce, April 25, 1956, p. 4.

Describes a commercial device manufactured by Air Glide Engineering Labs which uses gas lubricated bearings.

302. Mow, C. C., E. SAIBEL, "The Gas-Lubricated Sector Thrust Bearing," ASME Paper No. 58-LUB-5.

The object of this paper is to obtain an exact solution for a sector thrust bearing with side leakage and film variation in angular and radial direction, also taking into account the compressibility of the gas. (Auth)

The final form for the pressure expression is rather long and a computer would probably be required to obtain any significant amounts of data. The author shows the results of numerical examples in graphical form.

303. MOW, D. C. and E. SAIBEL "The Gas Lubricated Finite Slider Bearing" Proc. Sixth Midwest. Conf. Fluid Mech., Austin, Texas, Sept. 1959, pp. 383 - 405, AD-238253 Texas Univ. Press, 1959.

The object of this paper is to obtain an approximate solution for the gas lubricated finite slider bearing, and to investigate the effect of the bearing speed, slope of the inclination and aspect ratio on the pressure development, and load carrying capacity of the bearing. (Author).

Since for the calculation of the lubricating flow in a bearing the inertia terms of the Navier-Stokes equations may be neglected, the same expressions for the velocities result in a compressible and in an imcompressible lubricant. Differences only originate from using the continuity equation which in the case of compressible fluids contains the density of the lubricant. By inserting the velocities into this equation a Reynolds equation is attained with the product $p\partial p/\partial x$ instead of $\partial p/\partial x$ and $p\partial p/\partial y$ instead of $\partial p/\partial y$. Authors assume the flow to be isothermal and eliminate P by means of the state equation for ideal gases. So they obtain the nonlinear partial differential equation $\partial/\partial x\,[h^3 p\partial p/\partial x + 6\mu Uhp] + \partial/\partial y\,[h^3 p\partial p/\partial y] = 0$ ($h$ = film thickness; $\mu$ viscosity of the lubricant; $p$ pressure; $U$ velocity of the slider.)

As the slope of the inclination of a slider bearing $\varepsilon$ is very small authors use a perturbation method and insert the power series $p(x,y) = p_0(x_1 y) + \varepsilon p_1(x,y) + \varepsilon^2 p_2(x,y) + \ldots$ for p into the above equation. The equation is satisfied if the sum of the terms of equal $\varepsilon$-powers vanish. This condition yields partial differential equations which may successively be used for determining $p_0, p_1, \ldots$

The equation for $p_0$ is of elliptical form. Therefore, $p_0$ may have a maximum or a minimum at most on the boundary of the slider. Yet because there $p_0$ equals the ambient pressure $p_a$ it does not possess a maximum or a minimum anywhere and equals $p_a$ everywhere. By introducing the nondimensional quantities $\bar{x} = x/a$ (a = length of bearing), $\bar{y} = y/b$ (b = width of the bearing) and $P_n = Pn/Pa$ into the equations originating from the terms with $\varepsilon^1$ and $\varepsilon^2$ authors obtain equations for $\bar{p}_1$ and $\bar{p}_2$ which contain the dimensionless parameter $\beta = 6\mu Ua/p_a h_o^2$ besides $\alpha = b/a$ and $a/h_0$ ($h_0$ = outlet film thickness). At first they dealt with the case of an inifinite width slider. For the finite width slider they put $P_n(x_1 y) = \bar{\varphi}_n(x) + \psi_n(x_1 y)$ where $\bar{\varphi}_n(x)$ is the pressure for the infinite width slider and determined by the method of separation of variables.

The pressure distributions so calculated are lower and have

their maximum nearer to the outlet of the slider than in the case of the lubrication with an incompressible fluid. Further, with increasing $U$ the load capacity for a given geometrical configuration of the bearing seems to approach an upper limit whereas it is proportional to $U$ in the incompressible case.

304. MUELLER, P. M., "Air-Lubricated Bearings," Product Engineering Annual Handbook of Product Design, 1953, pp. J2-J5. Also appeared in Product Engineering, August 1951, Vol. 22, No. 8, pp. 112-115.

Journal, thrust, and "flat" bearings lubricated with air are described in this paper and their performance characteristics are discussed. The effect of clearance on pressure distribution between bearing surfaces is shown. The flow of air in these bearings takes place through two orifices in series. (Auth)

In Mueller's system a fixed and a variable orifice are separated by an intermediate pressure chamber. The author shows the flow depends on the area of the second orifice (bearing clearance) and the pressure in the intermediate chamber. Increasing the load causes the clearance, h, to be smaller which should decrease the flow. However, if the load is to be supported, the intermediate pressure must rise. This, when it happens, causes the flow to increase and thus become proportional to the load. By using a high supply pressure the flow through the first orifice into the intermediate chamber is always choked.

Since the flow is meant to be controlled by the load at all times it appears the purpose of the first orifice is solely to provide a restricted passageway into the intermediate pressure chamber which is necessary if the flow must increase with load.

Critics of this system say the flow may increase and decrease in turn thereby causing a spring-type action. The author claims, however, that this will not and does not occur if the intermediate pressure chamber is very shallow.

305. MUELLER, P. M., "Air Turbine Driven Spindle," Product Engineering Mar. 1952, Vol. 23, pp. 160-163.

This paper describes a simple air turbine, air lubricated bearings, and pneumatic speed governor combined in a drive for a high-speed internal grinder head unit designed to operate over a wide range of governed speed. (Auth)

This article contains sufficient design and development information to be of some value.

306. MUELLER, P. M., "Pneumatic Governor Design for High Rotational Speeds," Product Engineering, Oct. 1951, pp. 170-175.

Design of specific pneumatic governor suitable for small high speed air turbines. Detailed calculations of the size of

essential components and of governor's operating characteristics. Theory of the air gage and general rules for designing a pneumatic servo-controlled system to meet a required set of conditions. (Auth)

There is little more than mention of gas bearings in this article.

307. McBAIN, J. W., C. M. O'SULLIVAN, "The Development of the Air Driven Spinning Top as a Transparent Ultracentrifuge," Journal American Chemistry Society, 57, Dec. 1935, pp. 2631-2641.

In describing the development of a centrifuge, the problem of rotor stability is raised. Three types of rotor instability are described; precession, vertical vibration and horizontal wobble. Their causes and remedies are discussed.

As with most of the available literature on centrifuges, the topic of the gas-lubricated bearings is relegated to the background. No attempt is made to analyze the bearing problem mathematically. However, sufficient information is contained in the paper to make it a contribution to the general gas bearing problem.

308. McKINLEY, D. C., "Investigation of a Kingsbury Thrust Bearing Using Air as a Lubricant," Society Automotive Engineers Paper, Meeting, Jan. 19, 1953.

The design, development and testing of an air-lubricated Kingsbury type thrust bearing is described. The author assumes incompressible flow and computes the film thickness for two specific examples. He then briefly discusses the importance of a very good finish on bearing surfaces.

(Copies of this paper are not readily available.)

309. McNEILLY, V. H. "Design and Use of Pneumostatic Bearings" ASLE preprint Paper No. 60 AM 5A-2, April 1960, 16 p., also Design Abstracts May 26, 1960, pp. 151-155.

Applications of bearings lubricated by a film of compressed air, and characteristics of pneumatic bearings are discussed.

It is explained that "Pneumostatic" means "hydrostatic air", i.e., a hydrostatic bearing using compressed air rather than oil or water as its working fluid. The principles of operation are essentially the same as for hydrostatic bearings which use incompressible fluids. However, additional considerations must be given to expansion of the fluid, critical flow velocities, and vibration problems associated with compressibility.

The single-hole circular thrust bearing, the basic element for design of pneumostatic bearings with inherent orifice com-

pensation, consists of two parallel circular discs separated by a uniform gap through which air flows radially outward. To obtain effective bearing operation the separating force (and therefore the average pressure) must increase as gap thickness is decreased. An "inherent orifice" type of configuration provides the necessary flow restriction.

The possibility of two opposed discs (two such bearings opposing each other) is further discussed. To carry load a central element cannot be equidistant between the two opposed bearings but must be displaced. It is remarked, however, that total flow is independent of displacement because the increase in flow on one side is compensated by the decrease on the other. It is also shown how to design a complete journal bearing by proportioning a layout of holes to approximate radially symmetrical flow in a circular thrust bearing. Number and arrangement of holes are discussed.

310. NAHAVANDI, A. and F. OSTERLE "A Novel Form of Self-acting Gas Lubricated Thrust Bearing" Trans. ASLE, Vol. 4, No. 1, April 1961, pp. 124-130.

A nonpressurized parallel-surface gas lubricated thrust bearing is analyzed with the slider in steady spin and precession and found to develop a load capacity. The operation of this self-acting thrust bearing over a range of operating conditions is studied and the results applied to the so-called bevel bearing. The load capacity is obtained numerically by solving the Reynolds equation for a compressible lubricant in finite difference form on a high speed digital computer. It is found that this load capacity can be significant. (Auth)

311. NARASIMHA, R. "Nearly Free Molecular Flow through an Orifice" Guggenheim Aeronautical Lab., Calif. Inst. Technology, Pasadena, Calif., Oct. 1960; ASTIA No. AD-245 314; 23 p.

The purpose of this report is to make an estimate of the deviation of the mass flow $\underline{\dot{m}}$ through an orifice from its limiting free molecule value $\underline{\dot{m}}^{\,o}$. Using a method proposed by Willis, it is shown that this deviation is of the first order in $\mathcal{E}$, the inverse Knudsen number, defined as the ratio of the radius of the hole to the mean free path in the gas at upstream infinity. An estimate of the coefficient is obtained making some reasonable assumptions about the three-dimensional nature of the flow, and the value so derived, giving $\dot{m} = \dot{m}^{o}\,(1 + 0.20\,\mathcal{E}\,)$, shows fair agreement with the measurements of Liepmann. (Author)

312. NEMETH, Z. N. and W. J. ANDERSON, "Experiments with Rotating, 10-Inch-Diameter, Externally-Pressurized Air Thrust Bearings."

First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 361-382.

Experimental studies were made with three parallel surface, capillary compensated bearings at normal temperatures. Stationary plates contained four sector-shaped recesses. Ratios of recess radius to plate radius of 1/3 and 2/3 were investigated. Bearing airflows and plate clearances were measured at speeds to 14,500 rpm and loads to 4000 pounds. From measurements of bearing clearance close to the bearing axis, airflow, and pressure profile, it was deduced that the bearing plates dished possibly because of pressure forces and thermal gradients. It is shown analytically that plate dishing has a marked effect on the theoretical pressure profile, airflow, and load capacity.

313. NIGAM, S. D. and S. C. GUPTA, "A Boundary Value Problem for an Elliptic Equation in the Theory of Gas-Lubricated Bearings." Appl. Sci. Res., Hague, Section A, Vol. 9, 1960, pp. 463-4.

In a letter to the editor, the authors analyze briefly the Reynolds equation for pressure in the theory of hydrodynamic lubrication for the case of a gas-lubricated slider bearing working under isothermal conditions.

314. NISHIHARA, T., Y. SUGIMOTO, "On the Theory of Lubrication in the Journal Bearings," Report 31, Tech. Repts of the Eng Res Inst. Kyoto Univ., Kyoto, Japan.

The improvements in the mathematical treatment of Reynolds' hydrodynamical theory of lubrication by Sommerfeld and Gumbel have laid the path open to its practical application.

In case of cylindrical bearings, however, further investigations on certain corrections and approximations are necessary for a satisfactory agreement with experimental results. In the mathematical theory of Reynolds and Sommerfeld, the bearing length is assumed to be so great that the motion of the lubricant can be treated as two-dimensional.

It has been explained that, in actual practice, the lubricant can squeeze out through the edges. The present paper discusses the complete solution of the three-dimensional problem of lubrication in a journal bearing. (Auth)

Although the original analysis is for oil, air bearings are treated in the last sections. The conclusions state, "The results of analysis of the air bearing showed good agreement with the experimental data."

315. "North American Announces Use of Frictionless Air Bearings," American Helicopter, Vol. XX, No. 12, Nov. 1950, p. 17.

A short (200 word) article mentioning that air bearings are being used in components for guided missiles, etc.

316. OFFEN, A., "Laps," U. S. Patent 2 734 318, issued 1956.

The main object of the invention is to provide an improved method of, and apparatus for, internally lapping small round cylindrical holes (to 1/100 inch in diameter) especially those of great length. Exhaust air from the turbine drive passes between the spindle and bearings before being evacuated.

317. OHNO, T., O. TANIGUCHI, "Research on the Air Thrust Bearing, 1st Report," (In Japanese) Trans. JSME, Vol. 17, No. 63, 1951, pp. 31-36.

Several types of bearing have been used as air thrust bearings, but their behavior may not be the same or two different actions are combined in various ratios, namely lubrication by the air film (hydrodynamic) and that supplied by the uniform static pressure of air. In another special type the rotor is supported and also driven by the air. Under such circumstances, generally available data to design the air thrust bearing is lacking. We take up at first the type of two facing disks - one that is a stator and the other is a rotor, having a clearance with an externally supplied air film between them - and obtain some information concerning the properties of the air film, both experimentally and theoretically. (Auth)

318. OSPINA - RACINAS, E., "Pneumatic Toy," U. S. Patent 2 544 720, issued 1951.

An amusement device comprising a tube adapted for flow of a fluid jet thereout and a tubular conduit, one end of which conduit debouches into said fluid jet and is in aspirated relationship to said fluid jet so as to establish flow in said tubular conduit, the other end of said tabular conduit being in aspirating relationship to said fluid jet at a point further from the mouth of said tube than said first end. (Official Gazette)

Not much relationship to a conventional bearing. The ball being supported and raised by air, must re-enter the system through one of two openings from whence it is carried back to the starting point by the air stream.

319. OSTERLE, J. F., W. F. HUGHES, "High Speed Effects in Pneumodynamic Journal Bearing Lubrication," Applied Scientific Research,, Section A, Vol. 7, No. 2-3, 1958, pp. 89-99.

The steady-state operation of gas-lubricated journal bearings is analyzed for the effect of lubricant inertia on the pressure developed in the lubricant. Numerical results are given for a 180 degree partial bearing. It is found that the inertia effect can be significant in the laminar regime. (Auth)

The authors, in a series of mathematical papers, have attempted to make refinements to the equations of lubrication as generally known so that the numerical results arrived at will be more nearly in agreement with experimental results than they have previously been. Here they deal with the case of a 2 inch diameter shaft rotating at speeds up to 200,000 rpm. They show that to neglect the effect of lubricant inertia may introduce measurable errors in load carrying capacity when the peripheral shaft speed becomes 500 ft./sec or more. The correction acts to decrease the value of load arrived at which correction is in the right direction. An error in the determination of attitude angle is also incurred by neglecting inertia. No experimental verification is given.

320. OTT, P. W., "Gyro-Applications in Ballistic Missiles and Space Vehicles", Military Systems Design, Vol. 4, No. 6, Nov. - Dec. 1960, pp. 8 - 10.

This is a generally informative article in which the author reviews the functions of a gas bearing and how it operates; the applications of a gas bearing gyroscope; the ceramic gas bearing unit and its significance in the control of inconsistent torques; and gases found to be effective bearing lubricants.

Their relations to missile guidance systems, missile control systems and initial control in space missions are discussed.

321. PAIVANAS, J. A., "A Study of the Flow of Air in a Radial Diffuser," M. S. Thesis University of Buffalo, Buffalo, New York, June 1955.

The author made his investigations to acquire some understanding of the basic phenomena associated with the flow of air through a radial diffuser. Willis and Welanetz, also looked into this problem but not as thoroughly as Paivanas. A considerable amount of experimental work has done primarily at clearance of 1/8 inch. However, in some of the experiments, clearance was a variable and clearances as small as 0.003 inch were used. A one-dimensional theoretical study of the problem was made and compared to the experimental results. Agreement between theoretical and experimental results was not as good as the author would have liked it to be.

322. PAIVANAS, J. A. and T. Ranov, "An Experimental Study of Radial Flow of Air Between Parallel Disks", Partial Summary of M. S.

Thesis, Graduate School of Arts and Sciences, Buffalo Univ. 1955; Buffalo, N. Y., June 1961, 37 p.

The flow device investigated in this study consists of two narrowly-spaced, non-rotating, parallel disks between which fluid flows radially after entering in a direction normal to the disks from a central hole in the surface of one of the disks. In one part of the investigation, the distance between the disks is fixed, while in the other part one disk is guided so that it is free to move in a direction normal to the other. The flow in both cases issues from a hole of cross-sectional area which is large compared to the flow area between the disks.

A well-known phenomenon which is associated with this configuration is that the guided disk will not be forced away by the impinging fluid but will be attracted owing to the low-pressure region created by the flow as it enters into the narrow disk passage. The results of the investigation conducted for various weights of the guided disk are presented in the form of dimensionless plots of flow rate, static pressure distribution in the disk space, and disk displacement. The radial and transverse variation of velocity and pressure in the space between the disks were obtained for the fixed disk case and are also presented in the form of dimensionless plots.

The results are discussed from the standpoint of potential practical applications in the fields of flow control, flow diffusion and, in one of the limiting cases of geometry, to gas-lubricated thrust bearings. The analytical treatment of this flow case is discussed and a flow model based on the experimental information is proposed as an approach to a more satisfactory solution.

323. PAN, H. T., "Some Basic Aspects in the Theory of Hydrodynamic Gas Journal Bearings." General Electric Tech. Report for ONR, Contract No. NONR 2844(00), Sept. 14, 1960, 22 p. ASTIA No. AD-245 464

Three aspects in the theory of hydrodynamic gas journal bearings are discussed:

1. Compatibility Condition - For an isothermal gas film, it is shown that a unique algebraic relation exists between the forces acting on the shaft, the instantaneous time derivative of the film mass, and the instantaneous net leakage flow through the ends. Since all theoretical results of an isothermal gas film are to satisfy this condition it is given the name "Compatibility condition."

2. Influence of Shaft Whirl - By a Galilean transformation, the differential equation of Reynolds and its boundary conditions are written in terms of a set of coordinates fixed with respect to the whirl motion of the shaft. For a steady whirl motion, the transformed equation is independent of time. The compatibility

condition can also be expressed in terms of the moving coordinates.

3. Leakage Flow - The perturbation theory of Ausman is applied to the quasi steady-state problem in the moving coordinates. It is shown that the leakage flow does not vanish in the case of an infinitely long bearing. (Author)

324. PAN, C. H. T. and B. STERNLICHT, "On the Translatory Whirl Motion of a Vertical Rotor in Plain Cylindrical Gas-Dynamic Journal Bearings" General Electric Tech. Report for ONR, Contract No. NONR 2844(00) May 8, 1961, 25 p.

For the theoretical prediction of the dynamical characteristics of a rotor system, it is necessary to have an accurate knowledge of the bearing fluid film forces under dynamical conditions. With a small clearance ratio and at a moderate speed, the motion of the lubricant is governed by the generalized Reynolds equation. If the lubricant is a gaseous medium, the Reynolds equation is complicated by the compressibility effects, which include non-linearity and time dependence under dynamic conditions. In the case of a vertical rotor operating in plain cylindrical journal bearings, the steady whirl approximation is appropriate and time dependence in the Reynolds equation can be removed by a coordinate transformation. The form of the transformed equation is identical to the static Reynolds equation except that the compressibility number is modified by a factor which depends on the angular speed of the whirl motion. The attitude angle, in the presence of whirling motion, is quite different from the static attitude angle. On the other hand, the magnitudes of the forces are not very different. The steady whirl analysis may be used to determine the synchronous whirl motion of an unbalanced rotor. The phase angle between the fluid film force and the maximum film thickness plane is the complement of the attitude angle according to the quasi-static analysis. Experimental data is in excellent agreement with the results of the steady whirl analysis. Also, the modified compressibility number is reduced to zero at half frequency whirl, and the Reynolds equation, for an isothermal gaseous film with the small eccentricity ratio approximation, becomes identical to that of 2 liquid film. Since it has been established that the threshold of half frequency whirl for vertical rotors operating in plain cylindrical journal bearings is at zero speed, the same conclusion applied to the corresponding gas dynamic bearing. (Auth)

325. PANTALL, D., C. H. ROBINSON, "Gas-Lubricated Bearings in Nuclear Engineering, Part I," Nuclear Engineering, Feb. 1959, pp. 53-58.

The author summarizes briefly, the practical differences between bearings lubricated by liquids and gases with particular

reference to the hydrodynamic or self-acting type. (Pressure-fed bearings form the subject of a subsequent article, Part II.) In this article the accuracy of manufacture, load calculations, eccentricity ratio, and other parameters are discussed. Some mention is also made of whirl and associated phenomena.

326. PANTALL, D., C. H. ROBINSON, "Gas-Lubricated Bearings in Nuclear Engineering, Part II," Nuclear Engineering, Mar. 1959, pp. 123-128.

This, the second article of a series of two on gas bearings, deals with hydrostatic (externally pressurized) types beginning with an analysis of the important features of plain journals and concluding with a section on thrust bearings. (Auth)

327. PAVLECKA, V. "Aerostatic Bearings with Fluid-Dynamic Seals" U. S. Patent 2,916,332, Dec. 1959.

An aerostatic (hydrostatic) bearing having a rotor and a stator are described. The stator has a central cavity and a duct opening into the cavity for supplying working fluid under pressure into the cavity. The central cavity has a continuous side wall normally, when air bearing is in operation, forming a gap with the rotor of the bearing. There is also at least one auxiliary cavity on each side of the central cavity, the transverse-cross-section of which approximates, or approaches a circle,

Fluid escaping from the central cavity into the auxiliary cavity through the gap forms a vortex within the cavity, and a labyrinth seal between the rotor and the stator on the downstream side of the auxiliary cavity. The labyrinth seal has a gap opening into the auxiliary cavity; the gap being fluid-dynamically sealed by the flow of the fluid across the gap with the aid of the vortex formed by the fluid within the auxiliary cavity.

328. PEILER, K. E., "Sting-out Baffle for Glass Feeder Rotor Bearing," U. S. Patent 2 707 355, issued 1955.

The patent is for a system which will alleviate the deleterious effects of hot gases to machine parts in the making of glass. In the course of the discussion, mention is made of the use of gas bearings in glass making equipment.

329. PENICK, E. R., "Air Bearing," U. S. Patent 1 906 715, issued 1933.

The device patented is an externally-pressurized, multipad,, gas-lubricated bearing employing short capillary tubes leading from a common annular distribution chamber to the various recesses.

330. PERKINS, G. S., P. R. VOGT, R. R. WEBER, "Double Ended Journal Air Bearing," U. S. Patent 2 597 371, issued 1952.

The patent is issued for a double ended journal air bearing for possible use in a gyroscope. The bearing is capable of supporting the mass while allowing only a single degree of freedom.

331. PICKELS, E. G., "A New Type of Air Bearing for Air Driven High Speed Centrifuges," The Review of Scientific Instruments, Vol. 9, Nov. 1938, pp. 358-364.

The author describes a modification to the air-lubricated bearing of a centrifuge. The changes made were relatively simple and included the addition of a perforated disk below and inside the rim of the turbine wheel. The space between the disk and rotor then forms a pocket in which the pressure to support the load is contained.

332. FIGOTT, J. D., E. F. MACKS, "Air Bearing Studies at Normal and Elevated Temperatures," NACA paper presented at American Society of Lubrication Engineers Meeting in Boston, Mass., April 1953. Published slightly abridged and without derivation of equations in Lubrication Engineering, Vol. 10, No. 1, Feb. 1954, pp. 29-33.

Experimental studies were made with a six-inch outside diameter externally-pressurized, parallel surface, nonrotating air thrust-bearing at temperatures to 1000°F. Theoretical expressions describing the air flow through the bearing and the air flow through capillary tube resistances are presented in the form of design equations and curves and are compared with experimental results over a wide range of temperatures and loads. Results show that the load capacity is increased as the operating temperature is increased. (Auth)

The paper contains a theoretical analysis of the air-lubricated bearing and the results of experiments carried out at temperatures to 1000°F. Experimental and theoretical values of film thickness and air flow do not agree very closely and the authors attribute this, in part, to physical changes in the bearing surface resulting from the extremely high temperatures. Instabilities were also noted in one of the test bearings.

While there are many references made to the possibility of using air as a lubricant at high temperatures, this is, as yet, one of the few published records of experiments carried out along these lines.

333. POTTS, L. D., "Fluid Balancing Means," U. S. Patent 2 502 173, issued 1950.

The pressurized process fluid from a cryogenic pump is bled off and fed to the radial and thrust bearings where it counterbalances the forces acting on the rotor. According to the inventor the fluid does not enter the space between the journal and graphite material bearing. At the temperatures contemplated the fluid employed is a liquid. Whether it remains as such or changes to gas in the system is not specified.

334. RAICHLE, L., G. SCHULZE, "Thrust Balancing for Vertical Shafts", U. S. Patent 2 605 147, issued 1952.

The thrust load on a vertical rotor is balanced by causing the pressurized process fluid to act on a piston through which the shaft passes. When the load changes the motion of the shaft causes the flow path through a labyrinth system to be altered. The change in flow results in a corresponding change in pressure on the piston; thus automatically compensating for the unbalanced force.

335. RAIMONDI, A. A., "A Numerical Solution for the Gas Lubricated Full Journal Bearing of Finite Length" Trans. ASLE, Vol. 4, No. 1, April 1961, pp. 131-155.

Numerical solutions of Reynolds' equation pertaining to the finite length journal bearing with a constant unidirectional load and lubricated with a compressible fluid are given. Results are tabulated for the constant viscosity isothermal case for L/D values of 2, 1, and 1/2 and design charts applicable over the full range of compressibility number ( $\lambda = \mu UR/C^2 p_a$ ) are presented for eccentricity ratios ranging from 0.1 to 0.8. Differences between gas and liquid lubricated bearings are mentioned and the numerical techniques employed discussed. Use of the design charts is illustrated, and the numerical results are compared with an existing approximate analytical solution and some tests results available in the literature. (Auth)

336. RANDALL, R. E., "Thermodynamic Properties of Air: Tables and Graphs Derived from the Beattie-Bridgeman Equation of State Assuming Variable Specific Heats," ASTIA Document No. 135331.

The Beattie-Bridgeman equation of state was used to calculate several of the thermodynamic properties and flow process correction factors for air. The increase in the specific heats due to the vibration of diatomic molecules was included by assuming the molecules to be perfect harmonic oscillators. This report contains the equations used and the tabulated results of these calculations. Graphs are included to provide a general picture of the effects of temperature and pressure on the tabu-

lated quantities. In order to illustrate the use of the tables, the calculation procedures and the results of several calculations are included. These procedures and results are for isentropic expansions and flow through normal shock waves. (Auth)

337. RASMUSSEN, R. E. H., "The Flow of Gases in Narrow Channels," NACA TM 1301 Aug. 1951.

This report deals with the measurements of the air flow, T, per second per unit of pressure difference through various channels at average pressures of from 0.00003 to 40 cm Hg. Hydrogen, oxygen, carbon dioxide, argon, and air were utilized.

The flow channels consisted of:

1. Narrow annular slits between optically plane glass plates in Christiansen prismatic devices.
2. A rectangular slit between ground and soot-blackened glass plates.
3. A cylindrical slit between coaxial cylindrical surfaces of brass.
4. A porous plate (filter plate) of sintered glass.

It was demonstrated that the flow rate T at high pressure increases linearly with the mean pressure in the channel in agreement with the laminar-flow theory. The width of the annular slits, of from about 3 to 10$\mu$, was measured according to Christiansen's data by means of Herschel interferences; the optically obtained slit width was about 0.2$\mu$ larger than that obtained from the flow data.

At decreasing pressure, T assumes a minimum, if the mean path length is approximately equal to the slit width a; the minimum value $T_{min}$ is approximately equal to the value obtained by Knudsen's molecule flow formula. Hence, $\lambda_{min} \simeq a$, $T_{min} \simeq T_{Kn}$; this holds for all channels with well-defined slit width and for all gases.

At further decreasing pressure, T increases again and ultimately assumes a constant value $T_0$, when the mean path length has become substantially greater than the length of the channel. The most accurately determined test values of $T_0$ are tolerably agreeable with the values obtained from Clausing's formulas by an only approximately correct application.

It was shown that the quantity $T\sqrt{M} = f(\lambda)$ is approximately the same function of the mean path length for all gases for a particular channel, hence, independent of the gas. This rule may be of practical significance for determining the flow resistance of a channel for different gases within a random pressure zone.

The effect of the divergence from the cosine law on the molecule flow, identified by Knauer and Stern, was investigated. It was found that it amounts to only a few percent of the total flow.

The decrease of T from the value $T_0$ to $T_{min}$ is a consequence of the collisions of the molecules.

338. RAWLINS, J. A., "Air Lubricated Thrust Bearing," U. S. Patent 2 535 454, issued 1950.

This patent is by the same inventor as 339 below. This device differs from the other in that the principle of the movable blocks, to relieve the clearance and pass off solid foreign particles, is applied to hydrodynamic,gas lubricated thrust bearings.

339. RAWLINS, J. A., "Gas Lubricated Bearing," U. S. Patent 2 511 543, issued 1950.

The patent issued describes a hydrodynamic type gas-lubricated bearing which negates the probable occurrence of failures due to dirt in the gas. This is accomplished by making the stationary block in two parts which are held by spring pressure. The excessive pressures cause the blocks to move apart. Thus foreign particles cannot become embedded and cannot therefore cause binding or scoring of the bearing surfaces.

340. REETHOF, G., "Analysis and Design of a Servomotor Operating on High-Pressure Compressed Gas," Trans. ASME, Vol. 79, No. 4, May 1957, pp. 875-885, Done at MIT - USAF Contract No. AF 33(616)-2356.

The analysis, design, and development of a high-performance gas servomechanism suitable for aircraft and missile applications is described. The flow-control valve consists of two upstream orifices of fixed areas and two differentially variable downstream orifices. The areas of the variable orifices are controlled by a simple electromagnetic actuator. The fluid motor consists of two single-acting self-lubricating pistons which actuate the rocker-arm load assembly through push rods. Design parameters were obtained from the results of an analog-computer design study. The predicted transient response agrees very well with the experimentally derived rise time of 4 millisec. (Auth)

The purpose of the paper is to demonstrate a successful approach to the design of high speed pneumatic control systems. Since gas-lubricated bearings may prove to be particularly susceptible to damage from dynamic loading, a device such as described may be of value. In any event, the analysis of flows and system characteristics are straightforward and may find application to gas lubricated bearings.

341. REINER, M., "Research on the Physics of Air Viscosity," Contr AF 61(514)-871, Library of Congress PB 122,227, (1957). Proc. Royal Soc. A., Vol. 240,1957, pp. 173-188.

I. A Centripetal Pump Effect in Air

An instrumental arrangement is described which constitutes a centripetal air-pump. It consists of a hollow cylinder closed at the top and open at the bottom which can be brought into rotation at high speed about a vertical axis. When a receptacle filled with a heavy oil is lifted until the cylinder is partially immersed, the oil does not wet the cylinder, but an airgap is maintained between the walls of the cylinder and the oil. It can be seen that air is pumped from the outer atmosphere through this gap into the cylinder. This presupposes that the air must be in a state of stress, which includes elastic cross-stresses. It is shown that these stresses result from a stress-strain relation in which the strain is defined in Hencky's logarithmic measure. This confirms Maxwell's theory that air is an elastico viscous material possessing an elastic shear modulus, and therefore a finite time of relaxation. A rheological equation for air is proposed accordingly.

II. A Centripetal Airpump

An instrument is described consisting of two circular metal plates; one stationary, the other rotating opposite it with a very narrow gap between both. At certain high speeds the air is drawn in a centripetal direction into the gap. (Auth)

The author interprets his experimental results as being due to non-Newtonian properties in air. Taylor in discussing this paper points out that if the conclusion is correct, the Navier-Stokes equations do not adequately describe the mechanics of air flow, therefore, many of the aerodynamic investigations carried out in the past 20 years were improperly done.

Since the hydrodynamic theory of lubrication as postulated by Reynolds assumes the lubricant to be a Newtonian fluid, there is much of interest in Reiner's work and the outcome of it.

342. REINER, M., "The Physics of Air-Viscosity as Related to Gas-Bearing Design." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 307-318.

This paper is concerned with that action of gases which permits the development of positive pressure when (i) the bearing surfaces are parallel, and, at the same time, (ii) there is no supply of air under pressure from an external pump.

The action described is the result of a hitherto unknown effect in the laminar flow of fluids which may be named cross-effect, because it is a manifestation of normal stresses in cross-wide directions, i.e., in the direction of flow, in the direction of velocity gradient, and in the direction normal to both. An instrument showing the effect is described and an outline of the theoretical background is given.

343. RENTZEPIS, G. M. and B. STERNLICHT, "On the Stability of Rotors in Cylindrical Journal Bearings" General Electric Technical Report for ONR, Contract No. NONR a2844(00), May 15, 1961, 35 p., AD-251014

The regions of stability for plane cylindrical journal bearings have been determined analytically. The linear "Variational" equation of motion has been employed to obtain the stability regions bounded by families of load-carrying capacity and operating eccentricity curves. The results were applied to the "quasi-static" equilibrium case for gas lubricated cylindrical journal bearings of $\frac{L}{D} = 2$. They show that there exists a "minimum" in the stability curves, a prediction supported by experimental evidence. The results of this work seem to bridge together observation on stability at very small clearances and large ones. (Auth).

344. REYNOLDS, O., "On the Flow of Gases," Proc. of Manchester Literary and Philo. Soc., Vol. 25,1885, pp. 55-71.

This paper contains a discussion and the correct interpretation of results noted by Wilde. The author, making use of the concept of sonic velocity at the throat of a convergent nozzle, shows that the flow of gas (air) is independent of the downstream pressure when the ratio of downstream to upstream pressure is less than a specific critical value (0.527 for air).

345. RICHARDSON, H. H., "Dynamic Analysis of Externally Pressurized Air Bearings," MIT Dept. of Mechanical Engineering M. S. Thesis, Cambridge, Mass., 1955.

A method of analyzing and understanding the dynamic characteristics of externally pressurized air bearings is presented and is applied to a specific bearing configuration.

Theoretical developments are given, leading to predictions of steady-state and dynamic characteristics of an air-journal bearing for the case when the shaft is not rotating. For the test bearing, the linearized theory, as developed, predicted within 20 percent the experimentally determined steady-state stiffness, mass flow, and dynamic response to a sinusoidal load force.

The effects of shaft rotation were studied empirically, and it was shown that the tangential slipping between the journal and sleeve surfaces produced a stabilizing effect on bearing dynamics at least up to 60,000 rpm. Thus a bearing designed to be sufficiently stable when the shaft is stationary will be more stable when

the shaft is rotating.

Experimental curves of torque required to revolve an air bearing are presented for speeds up to 50,000 rpm. (Auth)

In this paper the author extends previous work (Richardson and Grinnell), to include dynamic characteristics of air bearings.. In turn, this work, which includes the derivation of the "dynamic spring constant" of the bearing, leads to another contribution. Other material, suggested either by this paper or perhaps even by Richardson himself, has come from Wiese and Currie.

346. RICHARDSON, H. H., "Static and Dynamic Characteristics of Compensated Gas Bearings," Memo No. R.M. 7401-1, MIT, Cambridge, Mass., April 2, 1957, Trans. ASME, Vol. 80, no.7, Oct. 1958, pp. 1503-1509.

A static and dynamic analysis of a general configuration of a compensated gas bearing is presented for the case in which the effects of shaft rotation on performance are negligible. The equations developed can be used quantitatively, and are particularly useful in assessing the effects on static and dynamic performance of changes in design parameters such as fluid properties, compensation schemes, and geometry. To illustrate the use of the equations developed, a comparison is made between two common types of hydrostatic gas bearings - the pool bearing and the inherently compensated bearing - and a design example for a specific bearing requirement is worked. (Auth)

This is an extension of Richardson's previous work since the same equipment and original assumptions are used. This paper contains no experimental verification of the author's work, but he states that based on previous work noted above, the type of analysis used is valid. He also notes in his summary that at high values of speed the hydrodynamic effects in the fluid film can become the same order of magnitude as hydrostatic effects. (His analysis takes no account of rotational speeds.)

347. RIEGER, N. F., "Air-Lubricated Bearings: A Review of Published Work," Journal Engineering Society, Nottingham Univ., Vol. 9, 1957-8.

The author gives a concise review of work in the field of gas bearings. All of the numerous references listed are contained in this bibliography.

348. RIEGER, M. F., "An Experimental Investigation of the Pressurized Air-Lubricated Journal Bearing in the High Speed Range," Inst. Mech. Eng. 1958, Discussed Feb. 3, 1959, The Chartered Mechanical Engineer, Nov. 1958, pp. 422-423. (Summary only)

Experimental apparatus has been developed and used to study the friction characteristics of an externally pressurized air-

lubricated journal bearing. The effects of variations in speed, load, diametral clearance, and inlet pressure have been studied over a wide range at high speeds. The experimental friction coefficients have been compared with those given by the well-known Petroff formula, and a reasonable degree of correlation has been found.

Bearing air consumption has been measured and a linear-relationship between air-mass flow and inlet pressure is indicated. Curves relating load-carrying capacity to various ratios of inlet pressures are included, the applied loads being carried by hydrostatic flotation in all cases.

The bearings used were plain, cylindrical bushes of diameter 1-3/8 in. and length 1-1/2 in. Compressed air was admitted through three sets of radial-inlet holes around the bush circumference, pressures being adjusted to keep the shaft and bush as close to concentric as possible. (Auth)

This report represents a comprehensive experimental investigation of the high-speed range. It has value as a guide to future designs of high-speed apparatus and as a means of verification when a full analysis of the finite, pressurized bearing is developed. (Auth - Chartered Mech. Eng.)

349. RIEGER, N. F., "The High Speed Air-Lubricated Journal Bearing," M. Eng. Sc. Thesis, Univ. of Melbourne, 1957.

(Paper not available for review as of July 1, 1959.)

350. ROBERTS, D. B., "Comparison of Experiments with Infinite Length Theory for Gas Lubricated Journal Bearings," Tech. Memo 93-69-37, North American Aviation, Los Angeles, Calif., Sept. 22, 1955.

(Technical Memorandum are prepared for internal use of North American Aviation and are not generally available.)

351. ROBINSON, C. H., F. STERRY, "The Static Strength of Pressure Fed Gas Journal Bearings, Jet Bearings," A.E.R.E. Report/ R/R 2642, Sept. 1958. Available British Information Services.

The operation of a jet-type hydrostatic bearing is analyzed; the analysis suggests certain parameters which are used in the presentation of experimental data. Methods of predicting the load carried by, and the flow requirements of, such a bearing are given. (Auth)

352. ROBINSON, C. H., F. STERRY, "The Strength of Pressure-Fed, Air-Lubricated Bearings," Part 1, A.E.R.E. Report ED/R-1672, Harwell, Berks, 1958.

The method of operation of an hydrostatic journal bearing is reviewed. An expression for the load carried and the gas flow from an infintely long porous bearing is deduced, and experimental results are plotted on the basis of parameters derived from the theoretical study.

Design curves for the load and gas flow are included. (Auth)

353. ROBINSON, C. H., F. STERRY, "The Strength of Pressure-Fed, Air-Lubricated Bearings," Part II, A.E.R.E., Report ED/R-1673, Harwell, Berks, 1958.

(Paper not available for review as of July 1, 1958.)

354. ROBINSON, G. M., "A Special Analytical Study of Air-Lubricated Bearings for Jet Aircraft Engines," Franklin Institute Lab Final Report F-A1914, Feb. 1957, prepared for NACA under Contract NAw 6473.

Design formulae and methods for a simple step bearing were derived and bearing loads encountered in maneuvers listed in the specification MIL-E-5007A were analyzed. These analyses and formulae indicate that air-lubricated bearings may be adaptable to aircraft turbojet engines. However, large bearings, small clearances, and large volumes of air will be involved. (Auth)

This is an unpublished report for NACA having as its major objective an analytical study of the feasibility of adapting air-lubricated bearings to aircraft turboject applications. The author derives equations for the laminar, isothermal, compressible subsonic flow of a perfect gas through a capillary, with and without momentum effects included and compares the two cases graphically. The viscous flow through thrust bearings of the flat, parallel disk type is then analyzed in a manner similar to that of Deuker and Wojtech. The flow equations which result are applied to the experimental data of Licht and Fuller and remarkable agreement (1 1/4% error) is found. The analysis and a discussion of the above are carried to simple recess type hydrostatic gas beariggs.

The author includes a short section on the typical loadings to be expected on the basis of imposed specifications. This is then followed by a numerical solution for load carrying capacity and required gas flow in a bearing which might be applied. Since the hypothetical bearing was not subjected to rigorous design

considerations, the author can and does discuss ways of modifying bearings to improve their performance characteristics.

As of July 1, 1959, this report was being rewritten.

355. ROTHE, H. C., "Air Bearings for Guidance Components of Ballistic Missiles and Their Production Aspects." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 346-360.

The author reports that the Army Ballistic Missile Agency employes air bearings in its guidance components for missile and space vehicles. The high accuracy requirements imposed on these components make the use of a low friction bearing a necessity.

The air bearings are used as the inner gimbal bearings on itabilization gyros and pendulous gyro accelerometers. Since the angular spped of the floated part is negligible the bearings have to be externally pressurized.

In addition to the low torque requirement, the bearings must function properly under missile flight conditions. These include thrust acceleration, changing in magnitude and direction, vibrations over a wide frequency spectrum, and changing ambient pressure. These conditions cause very unusual problems with respect to load capability and stability of the bearing.

After assembly each bearing is subjected to tests to determine the lowest pressure which will cause the bearing to float under one g acceleration and to determine the turbine torque as a function of its position against gravity under working pressure.

Besides these routine checks every new type of bearing undergoes many tests before it is released for manufacture. Vibrators are used to determine natural frequency and damping constants. Stability investigations are made in a vacuum chamber atop a centrifuge. Dummy cylinders with rows of holes connected to manometers measure the pressure distribution inside the bearing.

These tests conducted on many bearings during the last years have given the A.B.M.A. a good knowledge of the influence of the design parameters. It is claimed that today it is possible to design air bearings for the A.B.M.A. with the assurance that they will perform as designed. For several years these bearings have been manufactured in great numbers and in many sizes by private companies for the A.B.M.A.

Great pains were taken to set up a procedure which makes the manufacture a science, not an art. Close tolerances are needed with respect to roundness and cylindricity on the journal and the sleeve and with respect to squarenssss and flatness on the end plates. No Swiss watch makers are needed to produce the orifices for symmetrical air flow. The puncture of the cemented-on aluminum foil can be done by unskilled men. The influence of dissymmetry and possible misalignment of the tool is greatly re-

duced by puncturing every second hole and then turning the work piece 180° and finishing the other holes. Many quality control checks are used during the manufacture to prevent rejections of the assembled bearings. Air gages are used to check the critical tolerances. Flow meters are used to check the air volume passing through each ofifice.

356. ROTHE, H. C., "Externally Pressurized Gas Bearings" Mech. Engng. Vol. 83, No. 6, June 1961, pp. 45-48.

The author reviews the advantages and limitations, and the fields of application of the externally-pressurized and the self-acting gas-lubricatdd bearings. Design and physical principles are discussed for two missile applications utilizing externally-pressurized bearings: a gyroscope and a pendulum used on stabilized platforms to establish the local vertical with great accuracy.

357. ROUDEBUSH, W. E., "An Analysis of the Effects of Several Parameters on the Stability of An Air Lubricated Hydrostatic Thrust Bearing," National Advisory Committee ofr Aeronautics, TN-4095, 1957.

Equations are developed for the motion of a gas-lubricated hydrostatic thrust bearing, and solutions are obtained on a digital computer for air as the gas. Systematic investigations are made of various parameters to determine their effect on bearing stability. Bearing pad volume and rigidity appear as prime controlling factors. (Auth)

A mathematical analysis is used which permits the development of the equation of motion of the bearing. Then by actual numerical solution for particular cases the amplitudes of motion are investigated as function of time to determine if they decrease (stable condition) or increase (unstable condition) with time.

358. RUSTON, "Gas Bearing Circulator, Class NFB," Publication 9792 Ruston and Hornsby Ltd, Lincoln, England.

A four page piece of advertising literature on a commercial device employing gas lubricated bearings.

359. RUTHERFORD, R., M. H. TAYLOR and J. O. HIRSCHFELDER, "Viscosity of Two Component Gaseous Mixtures, II. Comparison of Experiment and Theory" Wisconsin Univ. Report WIS-OOR-29a, Aug. 23, 1960; ASTIA No. 245948, 32 p.

The report presents an addition to these authors' previous report on "Viscosity of Two Component Gaseous Mixtures", and it includes viscosity and diffusion data of binary gas mixtures. Three of sixteen gas mixtures which possess viscosity maxima, $HCl-CO_2$, $H_2-Xe$, and He-Xe, were not included previously. Tables give data on (1) gas mixtures showing experimental viscosity maxima, (2) mixtures not showing experimental viscosity maxima, and (3) experimental values of K versus theoretical values of $\alpha$ K, for both of the above (1 and 2) gas mixtures.

360. SASAKI, R., "Research on the Air Bearing," (In Japanese) Trans. Japanese Society for the Science of Fire Arms (Kahei Gakkaishi), Vol. 37, No. 1, 1943, pp. 1-44.

Results of extensive experimentation on air lubricated bearings are given in the form of tables and graphs. (There is little or no theoretical analysis presented.) Three test rigs were employed; in the first the shaft rotates, in the second the shaft is stationary, and in the third, conical surfaces permit thrust loads to be taken (on the rig with the stationary shaft judging from sketches.) Pressure distributions were taken with one row of taps when the stationary shaft design was studied. However, with the rotatable shaft a considerable number of pressure taps arranged entirely around the bearing had to be used. Static and kinetic coefficients of friction were determined along with load carrying capacity and pressure distribution. The effect of speed on the coefficients of friction is shown in applicable curves.

This paper was published during the years of World War II in a publication which evidently has since gone out of print. As a consequence, copies of the paper are limited and not readily available. Sasaki and Mori used a pressure tap device quite similar to the one shown here. They, in their work, also make much use of the coefficient of friction in presenting their results.

361. SASAKI, T., H. MORI, and OTHERS, "Air Lubricated Bearings and Their Utilizations," (In Japanese) Journal J.S.M.E., Vol. 60, No. 463, 1957, pp. 821-827.

The Navier-Stokes equation with inertia term neglected is used to derive the expressions for pressure distribution and rate of air flow. The general formulas are given for film thickness, bearing load and flow rate for the case when film thickness remains constant. Optimum designs of air bearings are discussed. Experimental results on coefficient of friction and frictional power loss are presented.

362. SASAKI, T., H. MORI and OTHERS, "Air-Lubricated Bearings for Spinning Spindles, 1st Report," (In Japanese) Trans. Japan Soc. Mech. Engrs., Vol. 21, No. 102, 1955, pp. 131-136.

The air-lubricated bearing which operates with slight friction and little or no temperature rise because of the cooling effect of air applied to spinning spindles which usually rotate at high speeds of 8000 to 12000 rpm. In this study, as the first step of the attempt, air-lubricated bearings are applied to spinning spindles without change in design of the ordinary spinning spindle which is lubricated with oil. The performance of such air-lubricated spindles under ordinary operating conditions is compared with those of oil-lubricated spindles. Experimental results show that the frictional power of the air lubricated spindle can be reduced to about 40% of that of the oil-lubricated spindle. (Auth)

363. SASAKI, T., H. MORI and OTHERS, "Air-Lubricated Bearings for Spinning Spindles, 2nd Report," (In Japanese) Trans. J.S.M.E., Vol. 21, No. 102, 1955, pp. 137-140.

Following the research of the first report, the design of the air-lubricated bearing of the spinning spindle was modified for the intended purpose. (Originally air was used in a standard oil-lubricated spindle bearing.) The operating characteristics of the new air-bearing were determined and compared with those of the oil-lubricated and unmodified air-lubricated bearings.

The experimental results show that the frictional power (loss) for the new bearing is some 30% less than that of the oil-lubricated bearing and about 50% less than that of the unmodified air-bearing. Thus the new bearing represents a significant improvement over the earlier versions tested. (Auth)

364. SASAKI, T., H. MORI and OTHERS, "Air-Lubricated Bearings for Spinning Spindles, 3rd Report," (In Japanese) Trans. J.S.M.E., Vol. 21, No. 102, 1955, pp. 141-144.

Following the previous reports, the newly-designed spindle with a radial air-lubricated bearing and a thrust bearing made with a steel ball were investigated. Such a design of thrust bearing was chosen owing to the fact that the air-lubricated thrust bearings with conical surfaces are not sufficient to reduce the frictional power as described in the previous reports. But the design of the upper radial bearing is left the same as it was in the 2nd report, because it had good characteristics. The experimental results show that the new spindle is superior to the other spindles especially in the range of high speed rotation, and its frictional power (loss) at 12000 rpm is about 25% of that of ordinary oil-lubricated spindles, 60% of the air-lubricated

spindle in the 1st report and 80% of the spindle in the 2nd report. And, moreover, by measuring the quantity of air flowing and calculating the power required to compress the air, the total power of the new spindle, that is the sum of the frictional and air-compressing power, is shown to be less than the power of the ordinary oil-lubricated spindle. This fact shows that the use of air-lubricated bearings is practical for spinning spindles. (Auth)

365. SASAKI, T., H. MORI, "Air-Lubricated Bearings with Capillary Air-Feeder Holes," Memoirs of the Faculty of Engineering, Kyoto University, Vol. XIX, No. 1, April 1957.

Capillary air-feeder holes of which each one is considered to possess the ability of two restrictions in series have been applied to air-lubricated bearings running at high speed. It has been concluded by the author that the air-lubricated bearing, having capillary air-feeder holes located in diametral symmetry, can be operated in quite a stable state and within extremely small coefficient of friction. This friction coefficient coincides perfectly with the value calculated from Petroff's equation.

In this article the authors consider bearings with more than one air-entry hole. The value of enlarging the capillary where it joins the bearing inner surface is discussed and the conclusion drawn that enlargement is not necessary if the proper ratio of air-entry hole radius to bearing radial clearance is used. The information presented in the paper is predominantely experimental. The theoretical work is taken primarily from previous work and consists only of relatively simple mathematics with some discussion.

366. SASAKI, T., H. MORI and OTHERS, "On the Air-Lubricated Spinning Spindles, 4th Report," (In Japanese) Trans. J.S.M.E., Vol. 21, No. 102, 1955, pp. 51-54.

The experimental set-up to obtain results for this report is similar to that described in Report No. 3. Graphs are given to show the frictional power loss and power required to supply the compressed air for lubricating the spindles at various air pressures and speeds. In comparison, it is shown the total power loss (frictional loss plus power to operate air compressor) is substantially less than that of an oil-lubricated spindle. The modified design gives improvement in performance over the one in Report No. 3.

367. SASAKI, T., H. MORI, "On the Characteristics of Air-Bearing," Memoirs of the Faculty of Engineering, Kyoto University, Vol. XIII, No. 1, Jan. 1951.

This is an experimental study of some of the factors effecting the performance of externally-pressurized air bearings. In one section the authors describe three means of determining the friction in the bearing and then use one or more of these methods in their experimental program. They measure friction values for various bearing pressures for two types of air inlet holes. These data are plotted in suitable curves. For all other curves the minimum friction value, (described in 369) is used when applicable. Among the factors investigated are bearing length, speed, clearance and angle of air inlet opening. Since curves of friction versus speed at various diametral clearances are shown for both air and oil lubricated bearings, a direct comparison can be made if desired.

The second part of the paper is devoted to the determination of air flow and pressure distribution in the bearing. The bearing shell used in these experiments had pressure taps arranged every $30^{\circ}$ around the circumference at specified distances in the axial direction. From the results the authors conclude that air flows into the bearing at the sonic velocity. This knowledge is then used to determine the air flow, the value of which agrees with that measured.

This is the authors' English version of a Japanese paper and one of the things one notes about their writing is the lack of a "summary" or "conclusions" which most of us are accustomed to. Their work appears to be quite well done with only minor bits of information missing. There is no attempt to relate the experimental results with any theory except very briefly in the case of air flow determination. The entire article could be summed up as a presentation of experimental results with insufficient written matter to exploit what was done.

368. SASAKI, T., H. MORI, "On the Characteristics of Air-Lubricated Bearing (Succeding Report)," Memoirs of the Faculty of Engineering, Kyoto University, Vol. XVI, No. II, April 1954.

The author states that it becomes possible to increase dynamic stability of the air-lubricated bearing and to reduce frictional resistance, when the air supply pressure from the air compressor and the cross-section area of the primary restrictor are properly designed and treated in relation to bearing conditions. (Auth)

This is one of a group of papers on air bearings by the same authors. In this as in other papers, they use two restrictors in series and determine the supply pressure and section areas by a minimum friction concept which is explained in detail in another paper. Since this article is related so closely with others of the group they could properly be read together.

369. SASAKI, T., H. MORI, KONDO, SATO, "On the Effects of a Restrictor before the Air-Hole of an Air-Lubricated Bearing," (in Japanese) Trans. Japan Soc. Mech. Engrs., Vol. 20, No. 90, 1954, pp. 105-108, Translated by C. Kim, Franklin Institute Laboratories, Phila., Pa., Sept. 1957.

It is generally known that the air-flow between the air-hole and the bearing clearance of the air-lubricated bearing is equivalent to the air-flow through a nozzle. In this case, when a restrictor that corresponds to the air-hole and bearing clearance is set before the air-hole, the pressure in front of the air-hole will increase or decrease with the decrease or increase of the bearing clearance, (in the same manner as the gage pressure in the high pressure type pneumatic gage), and then the eccentric motion of shaft will be controlled automatically. The effect of a restrictor before the air-hole was studied by measuring the coefficient of friction, and the optimum cross-sectional area of the restrictor. From this the air-supply pressure was determined. (Auth)

The authors' suggestion of determining the required air supply pressure on the basis of the minimum coefficient of friction is rather novel and interesting but as is pointed out, applicable primarily to systems with relatively light loads.

370. SASAKI, T., H. MORI, and OTHERS, "Research on the Air Bearing, 1st Report," (In Japanese) Trans. J.S.M.E., Vol. 17, No. 59, 1951, pp. 49-53.

Experimental results are presented on air-lubricated journal bearings; one with a radial air inlet and the other with an air inlet making an angle of $40^{o}$ with a diameter of the journal. Relations between two of the four parameters: speed of journal, coefficient of friction, air pressure and bearing clearance, are plotted in graphs. In estimating the coefficient of friction Karman's formula is used to calculate the air resistance. (Auth)

371. SASAKI, T., H. MORI, and OTHERS, "Research on the Air Bearing, 2nd Report," (In Japanese) Trans. J.S.M.E., Vol. 17, No. 63, 1951, pp. 16-21.

In this report, the coefficient of air-bearing friction measured by the pendulum method and the pressure distribution investigated mainly for the state of minimum friction, are described. The coefficient of friction can be reduced to minimum on the order of $10^{-3}$ for each bearing load by adjusting air supply pressure and this minimum value becomes larger with decrease of bearing clearance and increase of rotating speed. The pressure is distributed almost symmetrically with respect to the line of the air inlet hole, and no influence of rotating speed and bearing length are seen for the

pressure distribution. By measuring the quantity of flow and from theoretical considerations it is shown that the operating state corresponding to the minimum friction is non-eccentric rotation and the maximum air velocity at the outlet of the air inlet hole is the velocity of sound. (Auth)

372. SASAKI, T., H. MORI, and OTHERS, "Research on the High Speed Air-Bearing and on the Influence of Inlet Holes for the Air-Bearing." (In Japanese) Trans. J.S.M.E., Vol. 18, No. 74, 1952, pp. 51-56.

In the 1st and 2nd reports of research on the air-bearing, we discussed the measurement of the coefficient of air-bearing friction by the damping method with rotating disc, and the pendulum method, but the former was not suitable for high speed rotation, and the latter contained some error due to the moment caused by the air supply rubber tube. In this report, therefore, by making a newly designed balanced beam tester using a zero-setting method, we measured, accurately, the coefficient of air-bearing friction for the state of high speed rotation (12,500 rpm), and investigated the influence of bearing length and inclined angle of air inlet hole comparing it with the half ($180^{o}$) air-bearing. The coefficient of air-bearing friction can easily be made of $10^{-3}$ order by adjusting the air supply pressure for the high speed rotation of 12,500 rpm, but then the air pressure is required to be higher. The half bearing is superior to the full-circle bearing for stability with varying bearing load, but it is inferior in terms of frictional resistance, supply pressure, and quantity of flow. (Auth)

373. SASAKI, T., MORI, and OTHERS, "Research on the High Speed Air-Bearing and on the Influence of Inlet Holes for the Air-Bearing," (In Japanese) Trans. J.S.M.E., Vol. 18, No. 74, 1952, pp. 56-61.

In the paper, "Research on the Air-Bearing (2nd Report)," we stated that the air-flow through air supply inlet hole has large effects upon the air-flow in the bearing clearance and consequently influences the frictional characteristics. In this paper we proceded with the study of the air-flow just after the jetting-hole by measuring air pressure distribution under the low pressure of air supply; and varying the form and dimension of the inlet hole we inspected their influences on the frictional characteristics and the quantity of flow. Thus, it was shown that making the air supply slot longer along the axis of the shaft has more effect in reducing the frictional resistance than making the diameter of the air supply hole larger, and the flowing quantity is proportional to the product of periphery length of air hole, bearing clearance at the inlet and absolute pressure of

supply air. Based upon the above considerations, we revised the formula of the air-flow for air-bearing described in the second report. (Auth.)

374. SASAKI, T., H. MORI, "Theory of Journal Air-Bearing," (In Jananese) Trans. Japan Soc. Mech. Engrs., Vol. 19, No. 86, 1953, pp. 45-48. Translated by C. Kim, Franklin Institute Laboratories, Phila., Pa., Sept. 1957.

In the (hydrostatic) journal air-bearing, air supplied from either a single or multiple hole air-inlet, flows radially into the bearing clearance at first. It then flows longitudinally and lastly outwards from the ends of the bearing. Therefore, a three-dimensional analysis is necessary when the air-bearing is studied theoretically. In this report, analytical investigations were made for the condition of noneccentric rotation. This is important because it corresponds to the condition of minimum friction. Then the solution of the hydrodynamic equation was obtained by considering that the air flow corresponding to the condition of non-eccentric rotation, is equivalent to the two-dimensional potential flow. The theoretically obtained results coincide moderately well with the experimental results. This solution can be applied to the case of multiple air-holes. (Auth.)

In this, as in their other work, the authors proceed slowly but thoroughly. The mathematical analysis is made with the aid of a suitable transformation into the complex plane. The solution of Reynolds equation ariived at for pressure distribution is then molified to permit the use of additional inlet holes. The theoretical results agree with the experimental ones determined with a special bushing containing a sufficient number of pressure taps arranged both circumferentially and axially to give desired information.

375. SASAKI, T. and H. MORI, "Survey of Gas-Lubricated Bearing Research in Japan With Recent Developments in the Study of Externally-Pressurized Bearings." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 266-294.

The historical development of gas-lubricated bearing research in Japan, for both self-acting and externally-pressurized bearings, is briefly described. The conditions under which the Reynolds equation can be reduced to the Laplace equation are investigated. Analytical solutions of the pressure distribution of externally-pressurized concentric journal or parallel surface thrust bearings are obtained for compressible and incompressible fluids, for several bearing configurations, by means of complex potential functions. Flow rates, and approximate evaluations of the effects of eccentricity and sliding speed, are also obtained. A bearing design factor for restrictor compensated bearings is presented, and optimum

values for maximum bearing stiffness are determined. Comparisons are made between theoretical calculations and available experimental data.

376. SCHNEE, M., and E. J. WOHL, "Study of Fatigue Evaluations Procedures for Electron Tubes," Lab. Proj. 5032-B-3.14, Prog. Dept. 14, NE 091105, Oct. 11, 1956. Materials Lab., N. Y. Naval Shipyard, Brooklyn, N. Y.

Progress on a related Material Laboratory investigation which concerns the developmet of a novel shaker (in rudimentary form), permitting wide frequency range vibration and possessing little transverse sensitivity, is reported. Preliminary results indicated that 3/16" excursion of a (linear air bearing supported) 15 pound table is possible with as little as 10 watts at 10 cps. (Auth.)

377. SCHRADER, E. W., "Bowling Ball Serves as Air Bearing Journal in Discoverer Spin Tests," Design News, Vol. 16, No. 11, May 22, 1961, pp. 10-11.

The spin system employed in the early flights of the Discoverer satellite caused difficulties in recovering the re-entry body of the satellite. To correct this deficiency, a replacement spin and despin system utilizing cold gas was designed, built, and tested at Lockheed's Santa Cruz Test Base.

A mockup of the re-entry body was supported on a spherical air bearing, the journal of which was a bowling ball which was almost perfectly balanced and within 0.001 inch of being a perfect sphere. Compressed air entering through a series of small holes in the face of the bearing race created a low-pressure air cushion between the ball and the race. The tests were conducted in a temperature-controlled room which permitted the maintenance of desired tolerances in the air bearing. A photographic technique was employed to take measurements.

378. SCHUTTEN, J., H. BARON, T. VAN DER HAUW and P. J. VAN DEENEN, "Dynamic Measurement of Film-Thickness in Gas Bearings," Appl. Sci. Res., Hague, Vol. 7, sec. A, No. 6, 1958, pp. 429-436.

A method is described to determine the position of the sliding part of the bearing relative to the stationary one, as well as any vibration of the bearing within an accuracy of about 0.1 micromilimeter. by measuring capacitance changes between the sliding member and probes mounted in the stationary one. The resulting figure is displayed on an oscilloscope screen. The design for a gas-lubricated journal bearing is discussed.

379. SCIULLI, E. B., "A Bibliography on Gas Lubricated Bearings," The Franklin Institute Labs., Interim Report I-A2049-1, Dec. 1, 1957, Contract Nonr-2342(00), Task NR 097-343, ASTIA No. AD 147 733.

This bibliography is the result of an extensive survey conducted as one phase of a research program sponsored by ONR, in conjunction with other government agencies, to establish a technology for gas-lubricated bearings. The purpose of the survey was to evaluate the present state of the art and to establish a library of applicable technical papers to serve as ready references of work done in this field.

In order to include all the pertinent material available on gas-lubricated bearings it was necessary to review some literature from countries other than the United States. The bulk of this literature, primarily from England, France, Germany and Japan is obtainable in this country.

The entire contents of this report have been absored into the present bibliography.

380. SCIULLI, E. B., "A Bibliography on Gas-Lubricated Bearings," The Franklin Inst. Labs. Res. Devel., Sept. 1959, Report No. I-A2049-6, AD 147 733, 104 p.

The present compilation contains 290 applicable references. Wherever possible a resumé in English of each reference is included. In most cases the abstracts were taken verbatim from the author, translation being made when required. When necessary or desirable, resumés were prepared or revised by FIL staff members. Five indexes are provided. The Yearly and Corporate Name Indexes are the same as in the previous bibliography with, of course, the addition of the new references. The Subject Index, however, has been changed. The new Subject Index contains thirteen descriptively worded categories or headings specifically chosen to cover the many varieties and types of gas lubricated bearings. Of the other two indexes, one lists all the patents in numerical order and the other lists the country of origin of the reference when that country is other than the United States. (Auth.)

381. SERDUKE, J. J., and R. O. WEBSTER, "High Speed Bearing and Turbine," U. S. Patent 2 602 632, issued 1952.

The invention is a high speed bearing and turbine with a short shaft rotor. The turbine buckets are cut in the side of the rotor so that the impinging air constitutes a stabilizing force similar to that described by Brewster.

382. SEYFFERT, M., "Air Bearing Apparatus," U. S. Patent 2 671 700, issued 1949.

This invention appertains to novel and useful improvements in devices for use in fine measurements, cloee tolerance working and the like. It provides gas lubrication in rotary and thrust bearings for drills, buffers, polishing, and grinding machines which operate at exceedingly high speeds. (Auth.)

383. SHAW, M. C., and E. F. MACKS, "Analysis and Lubrication of Bearings," McGraw Hill, N. Y., 1949, Sect. 8-13, pp. 329-332.

Contains a brief mention of gas lubricated bearings.

384. SHEINBERG, S. A., "On the Question of Gaseous Lubrication of Rotating Shafts," (In Russian). Part 8 released April 2, 1945, pp. 175-206. The source of this paper cannot be determined. Copies are on file in the Friction and Lubrication Branch, The Franklin Institute Laboratories, Phila., Pa.

In Chapter I the theory of the plane slider bearing is developed. In Chapter II the experimental apparatus is described, the description includes that of each individual item such as galvanometer, stroboscope, etc. In Chapter III the pressure distribution in the air film is discussed. The apparatus and arrangement of the experiment are given . In Chapter IV the method of measuring friction torque and the results of experimentation are presented. In Chapter V the load carrying ability expression for air lubricated journal bearings is derived. The seventh and last chapter deals with industrial applications of air bearings.

385. SHEINBERG, S. A., "Experimental Investigation of Aerodynamic (Sliding) Bearings," (In Russian) Friction and Wear in Machines, Publication No. 6, Academy of Sciences of the USSR, Institute of Machine Construction, Moscow, 1950, pp. 182-299.

The first portion of the paper explains briefly the principles of operation and design of gas bearings. Later the experimental program is discussed including the methods and apparatus for determining film thicknesses, pressures and speeds. The experiments conducted on journal and thrust bearings are then described. The results obtained in these tests are compared with those from theoretical investigations.

386. SHEINBERG. S. A., "Gazovaia Smazka Podshipnikov Scolzhenia (Gas Lubrication of Sliding Bearings), "Trenie i Iznos v Mashinakh

Izv. Akad. Nauk. USSR, 1953, Vol. 8, pp. 107-204, Translated by C. Demrich; Edited by M. Wildmann. May be available from John Crerar Library.

In the present work the fundamental problem of gas lubrication (self-acting bearings) is examined and the theory of establishment of the lubricating layer described. In Chapter I there is derived, on the basis of the study of the lubricating characteristics of gases, the equation of spatial flow of a gas lubricant. Chapter II is devoted to the solution of the problem of the lubrication of bearings of infinite length, that is, the plane problem. In Chapter III the obtained solutions are extended with the help of certain assumptions to real bearings of finite length. In Chapter IV, finally, there is described the method of calculation of gas lubrication of bearings, and its results are verified experimentally. (Auth.)

387. SHEINBERG, S. A., and A. M. KHARITONOV, "Aerodinamicheskie opory dlia vysokoskoristnykh dvigatelii i turbin, (Air Lubricated Bearings for High Speed Motors and Turbines,)" Vestnik Mashinastroenia, Vol. 38, No. 9, Sept. 1958, pp. 14-17. (Also reviewed under "Hydrodynamic Gas Bearings in USSR" in Engng. London, Vol. 187, No. 4863, May 22, 1959, pp. 677-8).

Description of a high speed rotor with air lubricated bearings successfully tested in laboratory and industrial conditions, in the latter as an internal grinding head. The head assures high quality grinding and high efficiency. Design and manufacturing details.

388. SHEINBERG, S. A. and V. G. SHUSTER, "Vibroustoichivyi poristyi aerostaticheskii podpyatnik," (Porous Thrust Bearing Resistant to Vibrations,) Stanki i Instrument, Vol. 31, No. 11, Nov., 1960, pp. 23-27. Machines & Tooling, Vol, 31, No. 11, 1960, pp. 24-29.

This paper includes discussions of: resistance to vibrations of hydrostatic thrust bearings; design of porous bearings, for use with internal grinding spindles; simplified method of calculation; experimental verification of theory of porous thrust bearings; data on actual loads supported by bearings without air pads; particulars of practical interest concerning resistance to vibrations.

389. SHIRES, G. L., "Experiments with an Air Lubricated Journal Bearing," National Gas Turbine Establishment Memoradnum No. M. 49, May 1949.

Using a 2-inch diameter bearing, air is introduced through either a central ring of holes or two rings of holes placed symmetrically about the center of the bearing in the axial direction. The

effect of straight and flared inlet holes was determined as was the effect of diametral clearances. The holes were also connected by grooves and the effect noted. Among other variables chosen were speed (found to have a negligible effect on hydrostatic pressure distribution, up to surface speeds of 100 ft./sec.) and asymmetrical loading. Measurements were also made of mass flow and pressure distribution for various radial loads.

A 4-inch diameter (static) bearing with an eccentric stub on each end of the journal was used to obtain pressure distributions. Flow streamlines are shown in two photographs taken with the aid of oil as the fluid.

390. SHIRES, G. L,, "On a Type of Air Lubricated Journal Bearing," National Gas Turbine Establishment Report No. R. 61, Nov. 1949, also available as AERO Research Council Current Paper 318, London, 1957.

Experimental journal bearings have been constructed which will support a radial load when supplied with air at high pressure. The principles of this type of bearing are discussed, and some of the available experimental data analysed. The results are collated in terms of a non-dimensional parameter based on the theory of viscous flow between two adjacent surfaces and by this means are extrapolated to give performance figures for bearings outside the range of the experiments. The estimated performance is then compared with that of conventional bearings, and conclusions are drawn regarding possible applications of this type of air lubrication. (Auth.)

In the introduction, the author states that the theoretical solution of the load-carrying capacity of journal bearings, based on viscous flow theory, yielded values which were optimistic. It became necessary, therefore, to consider the problem in greater detail. The greatest detriment in the course of the experiments reported seemed to be complications of flow at the inlet holes. However, tests were conducted and empirical factors deduced from the data.

In the appendix the effect on the bearing of Reynolds' number, temperature, and centrifugal forces are each considered separately.

391. SHIRES, G. L., "The Viscid Flow of Air in a Narrow Slot," Memorandum No M. 46, Dec. 1948, National Gas Turbine Establishment, Reissued with Addendum as Aeronautical Research Council Current Paper, No. 13, 1950.

The properties of the viscous flow of air in a rectangular slot having a width large in comparison with its depth was investigated. The results of various tests are found to verify theoretical and empirical relationships between the pressure distribution

in the slot, the air mass flow and temperature, and the slot dimensions. Both laminar and turbulent flow are considered. (Auth.)

Flow experiments using air were performed with slots of various shapes (3) and the results expressed in the terms of the parameters $\lambda$ and Re. These were then compared with the results of experiments with incompressible fluids carried out by Blasius. The author reports that for laminar flow, the value he found for the resistance coefficient, $\lambda$, compares favorable with that for incompressible fluids. However, for turbulent flow the values of $\lambda$ given by Blasius are not, in general, applicable.

392. SIXSMITH, H.,"Air Bearing for High Rotational Speed," Machinery, Vol. 90, June 21, 1957, p. 1418.

A brief article describing the bearing developed by Sixsmith.

393. SIXSMITH, H., "The Theory and Design of a Gas Lubricated Bearing of High Stability," Doctoral Thesis, Reading Univ., Reading England.

The author designed (and later patented) a bearing having cavities leading to restricting orifices through which the gas need flow before leaving the bearing. According to the author, the pressure build-up in the pocket as the eccentric shaft approaches it is sufficient to combat the tendency of the shaft to whirl. Even at extremely high rotational speeds the shaft appears to be quite stable.

394. SIXSMITH, H., "The Theory and Design of a Gas-Lubricated Bearing of High Stability." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 418-434.

The work described was carried out during the development of an expansion turbine for use in an air liquefaction plant. For certain reasons the turbine rotor was made very small (9/16" diameter) and in order to reach the most efficient blade velocity it was necessary for the turbine to rotate at the high spped of 240,000 rpm. At such speeds conventional bearings are not practical. This difficulty may be obviated by the use of gas lubricated bearings, but these bearings were found to whirl at speeds much lower than the desired speed. It was also discovered that the forces on the turbine rotor, when using a gas lubricated bearing, were capable of exciting a whirl even if the shaft was prevented from rotating. It thus became necessary to design a bearing in which provision was made for the prevention of whirl. The method for doing this is described.

395. SIXSMITH, H., W. A. WILSON, and B. W. BIRMINGHAM, "Load Carrying Capacity of Gas-Lubricated Bearings with Inherent Orifice Compensation Using Nitrogen and Helium Gases," Nat'l. Bureau of Standards, Cryogenic Engrg. Lab., Boulder, Colorado, 1961, 35 p.

A static flat plate test apparatus was used to determine the load carrying capacity of circular thrust plates. The load carrying capacity of nine different pad and orifice combinations was determined experimentally using nitrogen and helium gas as the pressurizing medium. Actual load vs. plate separation curves were developed, at plate supply pressure ranging from 25 to 250 psig. The paper includes a description of the apparatus in addition to the curves which were developed for gas-lubricated bearing design. (Auth.)

396. SLATER, J., "Gas Spin Bearings for Gyroscopes," Military Systems Design, May-June, 1959, pp. 138-139.

A brief discussion is given of the application of gas bearings to gyroscopes and the advantages of these bearings over rolling element bearings. The work on which this article is based is attributable primarily to J. S. Ausman, M. Wildmann et al.

397. SLATER, J. M., V. A. TAUSCHER, "Zonal Ball-Air Bearing," U. S. Patent 2 617 695, issued 1952.

A zonal ball air bearing is described. The supported member "floating" between spherical seat bearings. Jeweled orifices, which are available commercially, are used in the design.

398. SLIBAR, A., "On the Theory of Self-Acting, Gas-Lubricated Journal Bearings." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 295-306.

Starting out from the non-linear Navier-Stokes equations for the flow of the gaseous lubricant, a product-solution for the journal of finite width is derived. To make the analysis tractable the dimensionless eccentricity ratio must be restricted to small values.

The product-solution, being built as an infinite sum in terms of increasing powers of the dimensionless eccentricity ratio, satisfies all the symmetry and boundary conditions imposed.

To allow for simple use by the designer, a graphical representation of the analytical results is presented using a dimensionless mean pressure. This characteristic pressure, for different values of diameter-to-width ratio , can be shown as a function of the Sommerfeld number.

400. SNELL, L. N., "Pivoted-Pad Journal Bearings Lubricated by Gas," U.K.A.E.A. Tech. Rept. No. 1GR-R/CA-285, 1958, 30 p.

In many of the tests described in this report the author determined the pressure contours in the gap between a 120° bearing and the shaft. The load was applied at points 40°, 60° and 80° from the leading edge and for the last two positions the ratio of load speed was proportional to $(\text{film thickness})^{-2}$. For the 40° position it was proportional to $(\text{film thickness})^{-3/2}$ and in all three cases the film thickness varied between $7 \times 10^{-5}$ and $6 \times 10^{-4}$ ins. Typical loads were up to 80 lb. and shaft diameters of 1 and 2 ins. were used in the tests. The pad width was 5 ins. and speeds were up to 3,000 rpm. It is stated that from the results of the work a successful bearing design for a speed 24,000 rpm was produced.

401. SNOPOV, A. I., "Ploskaia Zadacha Gidrodinamicheskoi Teorii Gazovio Smazkik" (The Two-dimensional Linearized Problem in the Theory of Gas-Lubrication." Izvestiia AN SSR, Otdel. Tekh. Nauk, Mekh. Mashinosta., No. 6, Nov.-Dec. 1959, pp. 14-20.

The author attempts to develop a method for solving the two-dimensional linearized problem in the theory of gas-lubrication. The method allows a solution of desired accuracy to be obtained, and the derived formulas are applicable to the case of bearings with random eccentricity. Conclusions: 1. The load is directed to the line of centers when the rotational speed and eccentricity increase. The load angle $\Psi$ is almost independent of the gas state. 2. The carrying capacity of the bearing cannot be increased indefinitely by increasing the rotational speed since $P \rightarrow \text{const}$ when $\theta \longrightarrow 0$. However, the carrying capacity of the bearing can be effectively increased by increasing the relative eccentricity, the diameter of bearing and the amount of lubricant. 3. In the adiabatic state of the gas the carrying capacity of the bearing is higher than in its isothermal state.

402. "Space Simulator Rides on Near-Frictionless Air Bearings. 5,000 Pound Structure Balances on a 5 inch Nickel Alloy Steel Ball Plated with Nickel." INCO Nickel Topics, Vol. 14, No. 4, 1961, p. 1 and 9.

News item on a Reaction-Control Test Vehicle (Boeing Co., Seattle) which pivots on a near-frictionless externally pressurized air-bearing. By now the air-bearing has had almost a year of trouble-free service on the RCTV.

403. STAHLHUTH, P. H., "Hybrid Gas-Bearings for Better Stability," Prod. Engng., Vol. 32, April 10, 1961, pp. 56-59.

This paper discusses the design and performance of a test rig found to be best suited for the study of the characteristics of hydrodynamic thrust bearings. This test rig permits a study of half-speed whirl and other stability phenomena, in addition to load capability. It incorporates provision experience relative to instrumentation, mounting calibration, secondary effect is due to rotor assembly details, and effects of rotor OD run-out on data reduction. The rig is instrumented to record film thickness, rotor motion, speed, radial load, film pressure, and lubricant flow pressure. Another important feature is the simulation of zero-g operation by rotating the bearing axis into the vertical plane. High loading conditions up to 10 g are provided by means of a pneumatic loading system.

404. STEIN, R. A., "On the Theory of Parallel Surface Thrust Bearings of Finite Width," ASLE preprint No. 61 AM 4 A-2, April 1961, 25 p.

A solution to Reynolds' equation for a parallel thrust bearing of finite width is developed. The lubricant density and viscosity are assumed to vary linearly in the direction of motion and are dependent upon the assumed temperature rise experienced in passing through the bearing. A general solution for the pressure distribution is developed for the case of arbitrary boundary conditons and a numerical solution is obtained for a particular set of characteristic boundary conditions. A comparison of the results with existing theories is discussed. (Auth.)

405. STERNLICHT, B. and R. C. ELWOOD, "Theoretical and Experimental Analysis of Hydrodynamic Gas-Lubricated Journal Bearings," Trans. ASME, Vol. 80, No. 4, May 1958, pp. 865-878..

This paper presents a numerical solution for finite width journal bearings and results of experiments conducted with air-lubricated hydrodynamic journal bearings. Comparison is made between theoretical and experimental results. Design formulas and recommendations for future studies also are included. (Auth.)

From the Navier-Stokes equation and the continuity equation for compressible fluid flow, the authors write Reynolds' differential equation for hydrodynamic lubrication in two dimensions and convert it to a dimensionless form. The resulting equation is first written as a difference equation from which an expression is then obtained for the pressure at the center of any grid element, for solution on a digital computer. The authors then discuss the desirability of maintaining a general pressure-density relationship involving the exponent $\delta$. However, to expedite calculations, this relationship is simplified by investigating only the isothermal case, $\delta = 1$. Theoretical and experimental results are presented for full journal bearings and correlation appears to be good for eccentricity ratios below 0.7. The solution of the original equation is promised for a later paper.

406. STERNLICHT, B., "Gas-Lubricated Cylindrical Journal Bearings of Finite Length. Part I - Static Loading." General Electric Tech. Report for ONR, Contract No. NONR 2844(00), August 15, 1960, 38 p., ASTIA No. AD 243 775.

This paper presents numerical solutions of the Reynolds equation for finite length, gas-lubricated cylindrical journal bearings under static loading. (The load has constant magnitude and direction with respect to the bearing.) The results are presented in dimensionless form which can be readily used by design engineers. Comparisons of the iterative solutions and the first-order perturbation and the "linearized ph" methods are made. The advantages and disadvantages of these methods of analysis are discussed. (Auth.)

407. STERNLICHT, B., "Gas-Lubricated Cylindrical Journal Bearings of Finite Length. Part II - Dynamic Loading," General Electric Tech. Rept. No. 60GL203, Contract No. NONR 2844(00), Sept. 9, 1960, 42 p., ASTIA No. AD-245 535.

This paper presents numerical solutions of the quasi-steady state, Reynolds equation for finite length, gas-lubricated, cylindrical journal bearings under dynamic loading. (Dynamic loading is defined by the condition where the journal center rotates and translates. This implies that the load changes in magnitude, direction or both.) Employing stationary and rotating coordinate systems, corresponding relations are established for the derivatives of force with respect to displacement and velocity using first-order perturbation solutions. Comparison of the iterative and first-order perturbation solutions are made. The results are presented in dimensionless form which can be readily used by design engineers for dynamic analyses of such phenomena as critical speed, synchronous whirl, half-frequency whirl, etc. (Auth.)

408. STERNLICHT, B. and R. C. ELWELL, "Synchronous Whirl in Plain Journal Bearings," General Electric Tech. Report No. 61GL37, Contract No. NONR 2844(00), January 30, 1961, 31 p.

The behavior of rotors in plain, self-acting journal bearings has been studied for the condition of synchronous whirl of a translatory mode. Synchronous whirl is an orbital motion of the journal or bearing at a frequency equal to the rotational frequency. The motion of the journal or bearing center is in the same direction as the rotation of the rotating members. The most common instance of this behavior in practice is the case of an unbalanced rotor.

The investigation was carried out both analytically and experimentally. The results of each of these studies are presented and compared to each other. It is seen that the experiments support

the analytical results to a degree sufficient for their general application.

Using the analytical results, which are presented in dimensionless form, it is possible to accurately calculate the amplitude of motion of any rotor as well as the phase angle between the load and point of minimum fluid film thickness.

The analysis covers compressible and incompressible lubricants for values of the bearing parameter $\Lambda$ between 0 and $\infty$ for L/D ratios of 1, 1.5, and 2. The limiting case of $\Lambda = 0$ corresponds to incompressibee fluids, making the results completely general. (Auth.)

409. STERNLICHT, B., H. PORITSKY and E. ARWAS, "Dynamic Stability Aspects of Cylindrical Journal Bearings Using Compressible and Incompressible Fluids." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 119-160. Also General Electric Tech. Rept., Contract No. nonr 2844(00), Feb. 1960, 103,p., ASTIA No. AD 230 243.

The paper presents solutions of Reynolds equation for cylindrical journal bearings in which the velocity of the journal center is considered. The inertia terms are neglected. Solutions are obtained for both compressible and incompressible fluids. Analysis of the steady state forces that exist in compressible fluid, externally-pressurized cylindrical journal bearings with one plane of feeding is also included. From these analyses the gradients of the radial and tangential forces with respect to displacement and velocity are obtained. The equations of motion for small and large oscillation in terms of these forces and gradients are set up, and stability criteria are established for small oscillations and also for large oscillations of a massless rotor. Sample calculations for threshold of instability are given and, where existing experimental data are available, theoretical predictions are compared with the results attained in practice.

410. STONE, W., "A Proposed Method for Solving Some Problems in Lubrication," Commonwealth Engineer (Australia), Vol. 9, 1921, pp. 115-122, 139-149. Available - Library of Congress.

This is a rather famous paper dealing with an experimental verification of Michell's theories of the action of thrust bearings. The apparatus was made of glass and the thrust shoes were fabricated from transparent quartz crystals. Air was the lubricant. Since the lubricating films were very thin and the angle of inclination small, they were measured by employing interference bands by passing sodium light through the apparatus. The author suggests that this method might be applied to cylindrical bearings. Considerable data are presented on speeds, loads, film thickness and angle

of inclination of the blocks. Typical data show slopes varying from a minimum of 0.137 minutes to a maximum of 1.93 minutes and mean film thicknesses varying from a minimum of 113 x $10^{-6}$ cm to a maximum of 1290 x $10^{-6}$ cm. Correlation between fact and theory is good.

There is an extended discussion on aspects of instability that were observed with certain of the test blocks. The author has studied these factors extensively and presents theory and data with the hope that certain problems may be solved that are associated with the application of air or other gases to the lubrication of machinery bearings.

411. STONER, G. H., "Air Bearing Gyroscope," U. S. Patent 2 474 072, issued 1949.

The invention is for gyroscope application and eliminates the need for a gimbal ring when the spin axis requires freedom only within a cone of $\pm$ 20° from the axis of the mount. The gas, introduced through a fixed hollow shaft with a ball at its end, enters an air chamber from which some escapes through "Bernoulli passages" formed by the ball and adjacent corresponding spherical surfaces formed in the wheel or rotatable member. The balance of the gas produces the rotation by escaping to the atmosphere through properly angled propulsion jets located in the periphery of the gyroscope. The best clearances for the Bernoulli passages (Bearing film thicknesses) are said to depend in part upon the particular design and the conditions of operation, and for optimum operation are best determined by experimental means.

412. STRUB, R. A., "Turbonaschinen fur Kernenergie-Anlagen" ("Turbo Engines for Nuclear Energy Installations") VDI-Z, Vol 101 No. 18, June 1959, pp. 747-752.

Nuclear reactors are cooled with water, heavy water, various gases and even liquid metals. For circulation of these cooling agents in a closed circuit, feeding machines are required, which must meet certain special requirements. It is necessary to protect certain engine parts from radioactivity that these coolants absorb in the reactor. Reliability of seals is also discussed. Several turbo engines have been developed which fulfill these requirements.

413. SIGIMOTO, Y., "The Theory of Air Bearings," (In Japanese) Trans. ASME, Vol. 17, No. 63, 1951, pp. 12-15.

The air bearing will run without the so-called lubricant and the friction is very low. In this paper, I dealt with, from a purely theoretical point of view, the use of air to diminish the

friction between bearing surfaces without any conventional lubricant.

In conclusion, air bearing is employed generally for high speed and light load.

The fundamental equation for air bearing is:

$$\frac{\partial}{\partial\theta}\left\{\rho\frac{\partial p}{\partial\theta}(\alpha+\cos\theta)^3\right\}+R^2\frac{\partial}{\partial z}\left\{\rho\frac{\partial p}{\partial z}(\alpha+\cos\theta)^3\right\}=\frac{6\lambda U}{m^2R}\frac{\partial}{\partial\theta}\left\{\rho(\alpha+\cos\theta)\right\}$$

where p is the pressure of air in bearing clearance, $\alpha$ is the eccentricity, $\rho$ is the density of air, R is the radius of journal, $\lambda$ is the viscosity of air, U is the linear velocity of sliding surface, mR is the distance between shaft center and bearing center, $\theta$ is the angle of coordinates, and z is the axis of coordinates. (Auth.)

414. "Supersonic Compressor," Sulzer Technical Review 3, 1958, pp. 62-65.

An industrial concern, Sulzer, in Switzerland has built a high speed compressor in which the bearings are lubricated with the gas being pumped.

415. TAFT, H., G. LILLIE, "Experiments with an Externally Pressurized Air Bearing," Bryant Chucking and Grinder Co., Research and Experimental Report No. 23, Springfield, Vt., 1950.

This is the first of a series of internal reports of experimental work done at Bryant Chucking and Grinder Co. on externally pressurized air-lubricated bearings. Using two opposed, static, parallel plate, thrust type bearings, the authors investigated the effect of bearing clearance, and number of air inlet holes, as well as the length and diameter of the holes. The results are plotted as load versus deflection for various supply pressures (20 to 50 psi). The work is summarized for 50 psi in three plots of "Maximum Bearing Modulus" versus each of the variables.

416. TAFT, H., G. LILLIE, "Experiments with an Externally Pressurized Air Bearing," Bryant Chucking and Grinder Co., Research and Experimental Report No. 24, Springfield, Vt., 1950.

This is the second in a series of internal reports of experimental work done at Bryant Chucking and Grinder Company on externally pressurized air bearings. For purposes of this report a simple, single, thrust type bearing was used both with and without a recess or pressure pool. Investigation was made on the effect of internal and external resistances and pool depths. The information gained was then applied to a journal bearing, which did not function as well as expected. A series of modifications and additional test resulted in a bearing which appeared to give satisfactory performance.

417. TAFT, H., and G. LILLIE, "Experiments with an Externally Pressurized Air Bearing," Bryant Chucking and Grinder Co., Research and Experimental Report No. 25, Springfield, Vt., 1950.

This is the third in a series of internal reports on experimental work done at Bryant Chucking and Grinder Company on externally pressurized air bearings. This report covers a series of static tests to obtain load deflection values for plotting graphs of a number of designs of cylindrical externally-pressurized air lubricated bearings for the purpose of determining approximately optimum designs for a wheelhead to be used in actual grinding tests. (Auth)

The authors tested the performance of a number of designs of pool type bearings (various pool depth and bearing lengths, etc.) using the slope of the load-deflection curves as the basis of comparisons. It would seem from their report that they were entirely satisfied that they had achieved a near optimum design of a bearing for a specified purpose.

418. TAO, L. N., "General Solution of Reynolds' Equation for Journal Bearing of Finite Width." Quart. Appl. Math., Vol. 17, No. 2, July 1959, pp. 129-136.

To obtain an exact and complete solution of the equation for finite bearings, Reynolds' equation, by suitable transformations of variables, is changed to Heun"s equation. This equation and its function as related to the problem, and its convergency are discussed. Pressure distributions and eigenvalues and their eigenfunctions are established. Calculational procedures are outlined.

419. TAO, L. N., "The Hydrodynamic Lubrication of Sector Thrust Bearing!" The 6th Midwestern Conf. on Fluid Mechanics, Sept. 1959, Texas Univ., Austin, Texas, 1959, pp. 406-416.

The present paper concerns the mathematical solution of the Reynolds' equation for a sector thrust bearing. An analytically exact solution is established in terms of Bessel and Lommel's (or Strive's) functions as well as some elementary hyperbolic functions. The bearing characteristics are then obtained. The major advantaggs of the present solution over previous solutions are (1) that no complex or imaginary arguments are involved in the mathematical expressions of the solution, and (2) that the bearing characteristics may be directly obtained by integrations in terms of some tabulated functions. Hence, any numerical computations of the problem are readily obtainable from some published tables in the literature. A numerical example of the problem is included. The calculated result is compared to other investigations. (Auth.)

420. TAO, L. N., "Theory of Lubrication with Turbulent Flow and its Application to Slider Bearings," Trans. ASME J. Appl. Mech., Vol. 27, Series E, No. 1, March 1960, pp. 1-4.

The governing equation of turbulent lubrication in three dimensions, equivalent to Reynolds" equation of laminar lubrication, is derived. The problem of a slider bearing with no side leakage is then analyzed. An exact solution in closed form is found. Bearing characteristics are also established. It is found that the Reynolds' number is an important parameter in the problem of turbulent lubrication. Furthermore, it is shown that laminar lubrication may be considered as the special case of the present study. A numerical example is also included. (Auth.)

42. TAUSCHER, V. A., J. M. SLATER, and J. EMMI, "Double Ball Gyro Precession Axis Bearing," U. S. Patent 2 644 727, issued 1949.

An externally pressurized gyroscope type, spherical, gas lubricated bearing is proposed. One difference from previous bearings is the use of "high pressure" (80 psi) air.

422. TAYLOR, G. I., and P. G. SAFFMAN, "Effects of Compressibility on Air Flow at Very Low Reynolds' Number," Journal of the Aeronautical Sciences, Vol. 24, No. 8, Aug. 1957, pp. 553-562.

This paper is a discussion of Reiner's paper, "Research on the Physics of Air Viscosity." In it, Taylor mentions the possibility of occurrence of two conditions which could have influenced Reiner's experiments.

(1) The effect of slight errors in the perpendicularity to the axis of rotation of either the stator or the rotor, and
(2) The efeect of rotor vibration in the axial direction.

Taylor then goes on to show mathematically that, with an incompressible fluid between the platen, neither the tilting action nor vibration could cause a pressure rise of the magnitude which Reiner observed. On the other hand, with a compressible fluid between the plates, either the tilting acting or vibration, or a combination of the two could account for the results noted by Reiner.

A discussion "On the Reiner-Taylor-Saffman dilemma " by M. Z. V. Krywoblock, appears on pp. 915-916 of the December 1957 issue of the Journal of the Aeronautical Sciences.

423. TIPEI, N., "Hidro-Aerodinamica Lubrificatiei (Hydro-Aerodynamic Lubrication)," Biblioteca Stiintelor Tehnice, Editura Academiei Republicii Populare Romine, Bucharest, 1957.

The bulk of this 695-page book is devoted to the development of mathematical expressions in the theory of lubrication with incompressible fluids; only the last 65 pages deal with gaseous lubricants. However, the work contained in the document is so extensive and so complete that experts in the field of lubrication consider it one of the best books on lubrication published to date.

The reader may note a similarity in titles of papers on gas bearings by Constantinescu and chapter subheadings in this book. Being a former student and presently a colleague of Tipei, Constantinescu would be expected to write and possibly extend the work already done.

The book is currently being translated from the Rumanian to English through the efforts od Dr. W. A. Gross of IBM and will be made available probably late in 1960.

424. TIPEI, N., "Consideratii Asupra Calculului Lagarelor Prin Alunecare, (Methods of Calculation for Sliding Bearings)," Bul. Stiint. Acad. R.P.R., Sectiunea de Stiinte Technice si Chimice 1952, 4, 3-4, 291.

(Paper not available for review as of July 1, 1959.)

425. TIPEI, N., "Ecuatiile Lubrificatiei cu Gaze (The Equations of Gas Lubrication,)" Comunicarile Acad. R.P.R. Bucharest, 1954, Vol. 4, No. 11-12, pp. 699-704.

(Paper not available for review as of July 1, 1959.)

426. TIPEI, N. and V. N. CONSTANTINESCU, "On High-Speed Self-Acting Gas Bearings," First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 225-241.

One of the main Operating ranges of gas bearings is that of high speeds. However, the compressibility of the gas influences its motion within the film. This compressibility must be taken into account, for a proper analysis of gas bearings.

Some problems concerning the analysis of gas bearings for various conditions, expecially at high speeds, are examined. The problem to determine the pressures in the case of finite dimensions of the surfaces for some one relative velocity is considered. With this purpose, an approximate solution is considered, which introduces a function of corrections with respect to the two-dimensional motion solution, determined by continuity conditions. In the case of high speeds, a method is proposed for the determination of pressures by the linearization of the differential equation of the problem. This involves taking into consideration a correction function of the pressure with respect to the asymptotic distribution of the pressure for

the high-speed case. In this way, cylindrical, as well as plane bearings can be studied.

The establishment of the three-dimensional solution is greatly facilitated, when simple analytical expressions are established for the pressure distribution in the case of infinite width bearings. In the second part of the paper these solutions are determined for various types of bearings, by using the linearization method of the pressure equation. In this way, simple, explicit relations are obtained for the pressures, with a sufficient degree of accuracy for the case of high speeds.

In the last part of the paper the behavior of gas bearings in the turbulent regime is considered, this regime being easily reached at high speeds. The study is performed by using the Prandtl's mixing length theory, which permits the determination of the velocity distribution, as well as the differential equation of the pressure. Taking into consideration a simple relation, (deduced in previous papers by the authors), between the mean velocity and the pressure gradient, it is shown that the pressure distribution in the case of two-dimensional motion can be deduced merely in integrals, for the turbulent regime.

426. TOBA, K. and E. SAIBEL, "The Finite Sector Thrust Gas Lubricated Step Bearing," ASLE preprint No. 61 AM 5B-2, April 1961, 33 p.

The principal object of this paper is to demonstrate the effect of compressibility of lubricant gas on the performance of a particular type of sector step bearing when the lubricant undergoes an isothermal process.

It is noticed that for small film thickness, deviation from the continuous medium such as the slip flow phenomenon may take place irrespective of the absolute magnitude of the flow density. Ween the Knudsen number, which is a measure of this phenomenon, is small, the flow may still be treated macroscopicallyl

By assuming a liquid having the same viscosity coefficient, the performance of the bearing for an incompressible lubricant is also evaluated and compared with that for a compressible lubricant over a range of the important physical parameters. (Auth.)

428. TOPANELIAN, E., JR., "Journal Bearing," U. S. Patent 2 696 410, issued 1954.

A porous material is made to form the bearing shell and one of the mating thrust surfaces. The lubricant, either gas or liquid is forced through the porous medium which, being tortuituous, offers a high resistance to flow and the effect is the same as having an infinite number of orifices. As described, the bearing as self-centering capabilities such as orifice-type bearings would have.

429. "Trapped-Air Thrust Bearing," Machine Design, Vol. 33, No. 12, June 8, 1961, p. 8.

News item on a type of air-lubricated bearing recently developed by Boeing Co., Seattle. It is stated that this externally-pressurized single recess step bearing supports an axially loaded shaft and allows it to spin freely at high rpm on a cushion of compressed air.

The new bearings hvee been operated with shafts ranging from 1/2 to 5 in. diam. and at speeds up to 100,000 rpm. Ambient temperatures have ranged from -330 to 600° F.

430. VANCE, M. D., "The Characteristics of a Multi-Orifice Journal Air Bearing," Curtiss Wright Corp., Report No. 49-6, also ASTIA ATI 56 113.

A compilation has been made of experimental data illustrating the characteristics of a multi-orifice journal air-bearing relative to stiffness and load capacity. (Auth.)

As the author states, this report contains experimental data. However, no firm conclusions are drawn and the paper proves to be merely a presentation of extensive data in appropriate curves. For practical purposes it appears to have value for only the type of bearing that was investigated.

431. VAN DEVENTER, J. H., "Counterbalanced Bearing," U. S. Patent 1 070 088, issued 1913.

In engines of the twin rotary type, (Compressors), the impactive and expansive force of the motive fluid supplied to the engine is brought to bear at one side of the rotors. This produces an excessive lateral thrust on the rotors and causes the bearings which carry the same to wear unevenly.

The general object of this invention has been: to provide a bearing which shall utilize the pressure of the fluid supplied to the engine to counterbalance the lateral thrust caused by the fluid entering the rotors of the engine. (Auth.)

The engine is adapted to be driven by steam. However, steam, compressed air, or any fluid under pressure may be used for motive power and for the bearings.

432. VITELLOZZI, W. J., "Report of an Investigation on Water and Steam Lubricated Bearings," EES Report, C-3229-C NS-633-008, June 9, 1950, ASTIA No. AD 147 283.

Journal bearings using steam or water for lubrication will find wise application in turbines, pumps, and other rotating machinery. The use of this type of bearing and lubricant would permit the design of exceedingly compact and reliable machinery. Immediate saving in weight and space would result through the elimination of seals, glands, lubricating oil sumps, pumps, coolers, filters, strainers, and piping.

This report covers the results of preliminary work in the development of journal bearings for service with steam or water lubrication.

To date, various materials have performed satisfactorily with water lubrication. Under steam lubrication, however, only one class of bearing material, namely, silver impregnated carbon, has shown promise of satisfactory performance.

The report concludes with the recomendation that this investigation continue, using the materials found satisfactory to permit establishment of material specifications and engineering desings. (Auth.)

433. VOGELPOHL, G., "Betriebasichere Gleitlager, Berechnungsverfahren fuer Konstruktion und Beitrieb (Sliding Bearings Calculations and Desing for Safe Operation,)" Springer, Berlin , 1958, for "Air Bearings," pp. 120-121, 128-129.

(Book not available for review as of July 1, 1959.)

434. WALKER, L.and F. OSTERLE,"A Centrifugal Effect Self-Acting Thrust Bearing," ASLE preprint No. 61 AM 5B-3, April 1961, 17 p.

A self-acting thrust bearing operating on centrifugal force effects is analyzed for both incompressible and compressible lubricants. A design which optimized the centrifugal force effect is established and found to be much simpler than the designs of conventional self-acting thrust bearings. The load capacity is determined and found to be significant but small compared to that of conventional bearings. (Auth.)

435. WALLOGREN, A. G. F., "Bearing," U. S. Patent 2 113 335, Issued 1938.

A description is given of a bearing within a bearing to be used principally where inaccuracies in alignment may occur. The shaft is continued in a gas-lubricated bearing which in turn is part of a cardan ring; the entire cardan ring unit being free to move within a second bearing shell.

436. WEBER, R. R., "Investigation of Dynamic Response of Hydrodynamic Gas Bearings," U.C.L.A., MS Thesis, Los Angeles, Cali ., 1952.

The author starting with the Navier-Stokes equation in vector notation, transforms it to cylindrical coordinates, makes various assumptions and introduces his boundary conditions to arrive at the equation for flow between flat parallel disks. At this point he introduces a density term and solves for the pressure distribution in the bearing showing it to be approximately linear across the sill (recess pressure to atmospheric pressure). Using this relationship, an expression for load carrying capacity is found. The equation for weight flow through the bearing is then equated to the weight flow through an orifice and after constant temperature is assumed, the film thickness is determined. The work is then applied to a discussion of opposed pad bearings.

Considering only the steady state parameters, the author imposes limits on the mimimum operating gap and applies a forcing function ($X = A \cos_{\omega} t$). The spring rate function ss approximated by typical functions and the coefficients determined by a curve fitting technique. Laplace transforms are then employed, to arrive at Duffing's equation, which can be solved by a method of successive approximation.

The restrictor (orifice) is "blamed" for certain departures between theoretical and experimental data.

The author concludes from his work that the compressibility effects of the gas trapped in the bearing can be considered negligeble for low frequency oscillations, and the dynamic response to oscillatory loads may be predicted on the basis of steady state characteristics.

437. WEBER, R. R., "The Analysis and Design of Hydrodynamic Gas Bearings," North American Aviation, Inc., Report AL-699, 1949, Los Angeles, Calif.

This report presents the fundamental theory of operation of single-disc pad, and journal types of gas bearing supports from the standpoint of gas consumption and load-carrying ability. An attempt has been made to illustrate the optimum or desirable values for the different bearing parameters. Two typical examples, a spherical bearing with four pads and a journal bearing, have been worked out to illustrate the design techniques which were developed. (Auth.)

The author, in a rather neatly prepared paper, carries the reader in a step process from the analysis of flow between parallel plates, eventually to the design of two types of externally pressurized gas-lubricated multipad bearings. His brief treatment of the preload effects on the spring rate of opposed bearings is made clearer by the use of suitable sketches and, as yet, has not been

discussed elsewhere in the gas bearing literature.

Journal bearings are treated as a series of rectangular pads. The momentum effects are considered negligible as is the tangential flow (between pads.) Since the entrance pressure of the gas and the film thickness, h, depend on the location of the journal in the bearing, the necessary equations are derived relating bearing inlet pressure, eccentricity and angular position of the gas inlet. The load-carrying ability of the bearing is then obtained.

Having dealt with the principles of bearing operation, attention is then directed to the design considerations with emphasis being placed on minimum power required on miniumu gas consumption. The two examples given, the design of a 4-pad supported sphere and the design of a journal bearing, contain numerical solutions.

438. WEIR, A., J. L. YORK, and R. B. MORRISON, "Two and Three Dimensional Flow of Air through Square Edged Sonic Orifices," ASME Paper No. 54-A-112.

In this investigation, the two-dimensional flow of air through rectangular and the three dimensional axisymmetrical flow of air through circular, square-edged sonic orifices was examined under pressure ratios ranging from 1.894 to 42.0 (upstream stagnation pressure/downstream static pressure). Mass flow measurements were made using a primary metering system, rather than another orifice or nozzle. Optical techniques were used to obtain pictures of the flow upstream, within the thickness of the orifice plate, and downstream of the orifice. Evidence is presented in this paper which indicates that square-edged sonic orifices can be treated as sonic nozzles by utilizing the concept that the air "turning the corner" of the orifice plate, in effect, makes its own nozzle. It is believed that this interpretation of experimental observations is in full agreement with established principles of aero- and thermodynamics. (Auth.)

439. WEIR, J. G., "Selected Bibliography on Precision Instrument and Fluid Bearings with Annotation," Materials Report No. 48, pp. 28-35, U. S. Naval Avionics Facility, Indianapolis, Indiana, March 14, 1957.

This bibliography is the result of an extensive survey of the entire field of precision instrument ball bearings and fluid bearings. The survey was made to evaluate the current state of the art as one phase of a bearing research program. The bibliography is intended to include all material pertinent to precision instrument ball bearings and fluid bearings. The material included on jewel bearings is less complete. (Auth.)

The section on fluid bearings, pp. 28-35, contains references on gas lubricated bearings. These references are included as part of this bibliography.

440. WELANETZ, L. F., "A Suction Device Using Air Under Pressure," Journal of Applied Mechanics - Trans. ASME, Vol. 78, June 1956, pp. 269-272. Discussion March 1957.

An analysis is made of the suction holding power of a device in which a fluid flows radially outward from a central hole between two parallel circular plates. The holding power and the fluid flow rate are determined as functions of the plate separation. The effect of changing the proportions of the device is investigated. Experiments were made to check the analysis. (Auth.)

Welanetz gives a more elaborate treatment to the problem first attacked by Willis in 1828. Using the general energy equation of steady flow and accounting for the various energy losses along the path, he derives the equations describing the characteristics of the device. He then attempts to verify his theory by experiments. Failure of the theoretical and experimental results to agree is attributed by the author to flow separation occuring at the transition from the small tube to the space between the plates (see Paivanas).

In his closure, after Zaid's discussion Welanetz also notes the possibility of shock waves occurring. The effect of this and other factors such as the compressibility of air are not included here in what the author refers to as a simple theory.

441. WESTINGHOUSE, G., "Vertical Fluid Pressure Turbine," U. S. Patent 745 400, issued 1904.

In a vertically mounted steam turbine, the vertical load is supported by the pressure of atmospheric air (or compressed air). The necessary pressure differential results from a partial vacuum caused by condensing the steam used to drive the turbine.

In this design, as in many of that date, no attempt was made to "design" an externally pressurized bearing of the types generally in use today (circa 1959). In general, use was made of the load carrying ability of a constrained volume of pressurized fluid with little attention paid to flow. The other extreme was to use the push effect of change in momentum directly over the fluid issuing from a jet.

442. WHIPPLE, R. T. P., "Herringbone Pattern Thrust Bearing," A.E.R.E., T/M 29.

(Paper not available for review as of July 1, 1959 )

443. WHIPPLE, R. T. P., "Theory of the Spiral Grooved Thrust Bearing with Liquid or Gas Lubricant," Atomic Energy Research Establishment T/R. 622, 1951.

The stated object of this paper was "to calculate the thrust for the spiral groove thrust bearing, and to find the optimum shape of the grooves at low speed." This type of bearing uses constant-depth grooves cut into the surface of a circular plate to generate, hydrodynamically, a thrust-carrying pressure distribution within the bearing. The load carrying capacity is derived analytically for both incompressible and compressible flow. The theoretical work is very complicated; even with simplifying assumptions, and the text is difficult to follow because all of the steps are not indicated or made clear. Some curves are presented for a particular spiral configuration which allow the designer to predict the load carrying capacity under varying conditions of viscosity, film thickness, relative velocity, ambient pressure and bearing dimensions.

444. WHITE, F. M., JR., B. F. BARFIELD, and M. J. GOGLIA, "Laminar Flow in a Uniformly Porous Channel," Journal of Applied Mechanics, Trans. ASME, Vol. 25, No. 4, Dec. 1958, pp. 613-617.

Presents the general solution of the Navier-Stokes equations for flow between porous parallel plates. The assumptions made in this analysis are as follows: (a) The flow is steady, viscous, and laminar; (b) Flow conditions do not vary in the z-direction (a two-dimensional problem is prescribed), (e) The condition of uniform porosity is simulated by prescribing a constant normal, velocity at the walls. (Auth.)

The use of porous materials has been considered for gas lubricated bearings. This reference is included as a possible source of contributory information.

445. WHITLEY, S., "Review of Research on Gas Bearings in the United Kingdom Atomic Energy Authority." First Intern. Symp. Gas-Lubricated Bearings, Washington, D. C., Oct. 26-28, 1959, pp. 30-70.

Two important characteristics of gas-lubricated bearings are load-carrying capacity and vibration properties. In this review, these two characteristics are discussed for various types of gas bearing.

The self-acting full journal bearing is discussed and the effect of an axial slot on its performance is described. It is shown that existing theories of load capacity give the best correlation with results if isothermal conditions in the gas film are assumed. Allowing for end effects, the measured performance is within about 10% of that predicted, and this is about the limit of present experimental accuracy. The most important vibration in the bearings is half-speed whirl, of which four separate modes have been distinguished and correlated by theory. The variation of half-speed

whirl with ovality in the bearing, and with circumferential grooves cut in the bearing has been measured.

The self-acting thrust plate described is of the spiral groove type. The hydrodynamic theory of the plate has been worked out by Whipple (1951), but experimentally observed values of load-carrying capacity have been lower than theoretical, often by as much as half. Vibration properties of this plate have been measured and adequately explained by treating the problem as one of forced, undamped, oscillations. An extra problem with thrust plates has been surface distortion due to the heat developed by friction in the gas film. It is shown that the distortion can be explained if it is assumed that 30% of the heat flows axially through the thrust plate.

The externally-pressurized bearings investigated in most detail have been those with simple orifice restrictors, as described by Shires (1949). The journal bearings consist of plain cylinders with two rows of eight orifices, and the thrust plate consists of a plain disc with six orifices drilled in equi-spaced circumferential grooves. The design of these orifices is described with reference to their effect on the stiffness of the gas film. Various modes of vibration of these bearings have been distinguished, particularly pneumatic hammer, synchronous whirl and half-speed whirl. It has been found experimentally that pneumatic hammer occurs when the critical pressure ratio across the orifice is exceeded. The synchronous and half-speed vibrations of the shaft can be either cylindrical or conical, and experimentally observed values are related to theory.

446. WHITLEY, S., "Improvements in or Relating to Gas Lubricated Journal Bearings," Great Britain Pat. 873 202, July 19, 1961, 7 p.

This invention describes a gas lubricated journal bearing having a bearing surface for supporting a rotatable shaft fitting in the bearing with a clearance between the bearing surface and the shaft. The bearing has in axial sequence from one end: a circumferential groove in the bearing surface with a hole for venting gas from the groove; and a pocket in the bearing surface with a hole for feeding pressurized gas to the pocket and an opening adjacent the pocket.

This gas lubricated journal bearing according to the invention may also have in further axial sequence from the pocket another circumferential groove in the bearing surface with a hole for venting gas from the groove, and another circumferential ring of orifices for feeding pressurized gas to the clearance.

It is also envisaged that the journal can be modified to incorporate a sleeve gland to prevent escape of gas from a pressurized system.

447. WHITLEY, S. and C. BETTS, "A Study of Gas-Lubricated, Hydrodynamic, Full Journal Bearings," Brit. J. Appl. Phys. Vol. 10, No. 10,

Oct. 1959, pp. 455-463.

$H_2$, $N_2$ and Ne which give large viscosity variation were used in investigation of load-carrying capacity and half-speed whirl. Argon and $CO_2$ were also used to investigate the ratios of specific heats. Bearings were plain cylinders with a longitudinal groove cut into upper surface extending over half the bearing length.. It was previously shown that groove improved half speed whirl characteristics. Tests without the groove showed that it does not affect load capacity.

448. WIESE, B. B., "Development of Design Information for Externally Pressurized Gas Bearings," Sc.B. Thesis, MIT, Cambridge, Mass., 1956.

By determining the effect of changing the clearance, design information is developed experimentally for a specific hydrostatic air bearing with inherent orifice compensation (see Richardson). Results of tests for bearing supply pressures to 400 psig are presented. (Auth)

The testing reported appears to be part of a broad program being carried out at the Dynamics and Control Laboratory of MIT. The data collected by the author is extensive and it should prove to be a valuable contribution.

449. WIGHTMAN, L. W., "Air-Driven Spinners," Machine Design, Vol. 20, No. 5, May 1948, pp. 121-125.

The author tells of the difficulties he experienced in building a high rotating speed machine for testing commutators. He admits rather frankly that some of the problems were solved by cut and try and others strictly by accident. In the end, an acceptable working device was evolved.

A bearing designer would do well to consider the difficulties encountered and described here.

450. WILCOCK, D. F., E. R. BOOSER, "Bearing Design and Application," McGraw Hill, N. Y., 1957, pp. 356-366.

Contains a small amount of information on gas bearings.

451. WILCOX, R. M., "Air Bearing," U. S. Patent 2 683 635, issued 1954.

This patent contains many ideas. The inventor points out various methods by which the stability, load carrying ability and stiffness of the externally pressurized gas bearings may be improvvd . These methods include the use of porous materials and shaping of the bearing surfaces. While many versions of these methods are

presented, the basic ideas are to provide a restriction to gas flow before it enters the space between the bearing surfaces or before it leaves the bearing surface, to divorce the supply from the film and to keep the volume of "trapped" gas to a minimum.

While there is no extensive mathematical treatment given, the discussion of theory concerning vibration of gas bearings appears to be thorough and sound. For other work on stability of hydrostatic bearings see Licht.

452. WILDE, H., "On the Velocity with which Air Rushes into a Vacuum, and on Some Other Phenomena Attending the Discharge of Atmospheres at Higher into Atmospheres of Lower Density," Proc. Manchester Literary and Phils. Soc., Vol. 25, 1885, pp. 17-34.

This is a presentation of experimental results of air-flow through a small opening. In his work the author experienced the effect of a critical pressure ratio but did not recognize it as such. Since the numerical data are relatively simple to reproduce, the paper has, perhaps, only historic value. For a more complete discussion of the experiment, and the correct interpretation of the results see the reference by Reynolds.

453. WILDMANN, M., "Experiments on Gas Lubricated Journal Bearings," ASME Paper No. 56-LUB-8.

Experiments performed on hydrodynamic gas-lubricated journal bearings are described, and results obtained are presented. During these experiments, radius, gap, length, speed, ambient pressure, and ambient gas were varied, and the effect of each variable on bearing deflection (eccentricity) and attitude angle noted. Axial and radial pressure distributions also have been obtained. (Auth)

The author approaches his problem in a critical manner, attempting to achieve utmost accuracy and precision in his experiments. Many probable sources of error are noted and their effect on the data evaluated. The experimental results are well presented in suitable curves. However, the discussion of them is rather abbreviated and some parts of the results left unexplained.

From his data, the author expects to obtain empirical relations between the various parameters affecting compressible fluid lubrication and with these predict the performance of such bearings. This work will be published in another paper.

454. WILDMANN, M., "The Behavior of Gas Lubricated Journal Bearings," M.S. Thesis, UCLA, January 1957.

A perturbation solution to the differential equation describing the behavior of a full gas-lubricated journal bearing of

infinite width is obtained. An exact solution to the same differential equation for the limiting case of infinite speed is also obtained. From these solutions, expressions for load capacity, attitude angle and friction forces are derived. The expressions are then compared to expressions for a similar bearing using a non-compressible lubricant. This comparison shows that there are large differences in the behavior of bearings using compressible and non-compressible lubricants. (Auth)

In this thesis, the effect of an association between the author and Ausman is noticed in that a perturbation solution is obtained for the equation of hydrodynamic lubrication with compressible fluids. In fact, here the author carries the solution a step further and includes third order terms which Ausman neglected.

In the appendix the author carries out the perturbation solution in a step by step process for the first, second and third order solutions.

455. WILDMANN, M., "The Load Capacity and Attitude Angle of Gas Lubricated Journal Bearings," Presented June 18, 1958, ASME Semi-Annual Meeting, Detroit, Michigan.

From experiements performed on gas lubricated journal bearings, semi-empirical equations giving load capacity and attitude angle of these bearings are derived. These equations are then compared to available gas bearing theory and it is shown that for small eccentricities, the equations obtained are adequate to predict the performance of gas lubricated bearings. (Auth)

The reader should take particular note that the author is presenting semi-empirical relations. The data are taken from previous work by the same author.

456. WILLIS, REV. R., "On the Pressure Produced on a Flat Plate when Opposed to a Stream of Air Issuing from an Orifice in a Plane Surface," Trans-Cambridge Phil. Society, Vol. 3, 1828, pp. 121-140. (Microfilm or photostat available from Library of Congress.)

The author attempts to explain the suction effect produced when air flows between two flat disks. By comparing the phenomenom taking place with that which occurred in an experiment explained by Hanksbee in 1719, he concludes that there is a rarefication (and therefore a lowering of pressure between the plates) due to the "jet" action.

This was one of the first scientific type experiments conducted on what is now termed a vaneless radial diffuser. That the problem is still of interest is evidenced by the recent paper by Welanetz.

457. WOOD, W. H., "Counter Balance for Journals," U. S. Patent 466 645, issued 1892.

Provision is made for automatically varying the gas pressure in a hydrostatic bearing to compensate for increased load.

458. WOODROW, J., "The Stability of Gas Bearings," A.E.R.E. E/M-35, July 11, 1950, 2 pages. Available USAEC on microcard.

In gas bearings involving divergent flow, a rise in pressure along the channel due to the Bernoulli effect, is superimposed on the pressure drop due to viscosity. Under certain conditions this leads to an unstable gas film. A preliminary investigation into this effect was made and is presented. (Nuclear Science Abstracts 13-5643)

459. WORDSWORTH, D. V., "The Viscosity Plate Thrust Bearing," A.E.R.E., E./R. 2217, Oct. 1952.

In Part 1 of the report, the aerodynamic theory of viscosity plate bearings is considered. Taking into account as many aerodynamic effects as possible, a new method of performance prediction is developed. The method is a simple one and easily used. Results given by it agree quite well with the existing one by Whipple. However, neither of these methods predicts the experimental results within an accuracy of 30% at speeds below 9000 rpm. At higher speeds there is no correlation at all. The theoretical curves show that the thrust is a linear function of speed throughout the entire range whereas the experimental curves indicate a decided change in slope at about 10,000 rpm from which point on the thrust is nearly constant for all speeds. The author being acutely conscious of this discrepancy attempted to find an explanation for it and in Part 2 investigated the effects of centrifugal action on the gas, heating of the gas due to frictional losses, the ratio of bearing clearance to the mean free path of the gas molecules (see Burgdorfer) and finally distortion of the grooved plate under pressure load. The last of these is shown to have a considerable influence as plate deflections reach a maximum of about five times the nominal gap and moreover vary considerably with radius and around the disc. The author concludes that the theoretical methods discussed, while evidently still valid, are not applicable to the experiments conducted since they are based on constant plate clearance and unable to cope with the elastic effects noted. (Author-Paraphrased.)

460. WUNSCH, H. L., "Design Data for Flat Air Bearings," Metalworking Production, Sept. 26, 1958, pp. 1697-1704.

A fundamental investigation on air bearings is being carried out by the Mechanical Engineering Research Laboratory, and as a first step tests have been carried out on one form of flat air bearing. This article gives the relationships that have been derived between design parameters, and illustrates their application with a design example. (Auth)

461. WUNSCH, H. L. "The Design of Air Bearings and Their Application to Measuring Instruments and Machine Tools", Paper presented at the First Conference on Machine Tool Design and Research, Birmingham, England, September, 1960.

(Paper not available for review as of July 1, 1961).

462. YEN, K. T., "On the Compressibility Effects of the Lubricant for Two-Dimensional Slider Bearings." Trans. ASME - J. Appl. Mech., Vol. 27, Series E, No. 4, December, 1960, pp. 609-12.

An analytical study of the compressibility effects on the characteristics of two-dimensional slider bearings is made. By the variational method, it is shown that for a given bearing length, no optimal film shape of the bearing can be found to yield a maximum total load. Analysis of the numerical results carried out for stepped films with a compressible lubricant under isothermal compression or expansion indicates that this anomaly is due to the nonlinear nature of the compressible problem. By considering a modified variational problem, it is further shown that stepped-film bearings with isothermal lubricant still yield the maximum total load for a given mass flow rate passing through the bearings, but the exact shape of the optimal stepped film is found to depend on the value of the maximum pressure. (Auth)

463. YOSHIRA, K., S. NORIMUNE, "Theory of Lubrication by a Compressible Fluid with Special Reference to Air Bearing," Second Japan National Congress Appl. Mech. 1952, Science Council Japan, Tokio 1953, pp. 267-270.

(Paper not available for review as of July 1, 1959.)

464. ZAID, M., Discussion of "A Suction Device Using Air Under Pressure," by Welanetz. Journal Applied Mech., Trans. ASME, Mar. 1957, pp. 156-158.

The author discussing the paper by Welanetz, notes that two pressure forces were neglected in the original analysis and proceeds

to make the necessary corrections. However, his theoretical results differ from the experimental ones even more than do those by Welanetz.

Both authors agree that an even more comprehensive theory is required.

SUBJECT INDEX

Numbers in parantheses indicate the number of the respective abstract in The Bibliography.

Externally-Pressurized Thrust Bearings of the Dummy or Piston Types

(37) (48) (150) (240) (334) (431) (441)

Externally-Pressurized Thrust Bearings of the Flat Plate (Including Recesses) Types

(2) (7) (8) (9) (11) (13) (17) (18) (22) (37)
(44) (52) (54) (75) (79) (91) (92) (95) (96) (97)
(98) (116) (117) (120) (1212 (122) (131) (139) (140) (144)
(148) (153) (155) (156) (158) (160) (162) (166) (173) (194)
(195) (196) (216) (218) (227) (228) (229) (230) (231) (238)
(239) (240) (241) (242) (243) (244) (246) (249) (260) (262)
(265) (269) (27o) (272) (273) (274) (275) (284) (285) (286)
(292) (293) (294) (300) (304) (306) (307) (309) (312) (317)
(321) (322) (331) (332) (333) (345) (346) (354) (355) (356)
(357) (360) (361) (375) (376) (382) (388) (395) (415) (416)
(417) (429) (437) (440) (445) (449) (451) (456) (457) (460)
(461)

Externally Pressurized Thrust Bearings of The Spherical or Conical Types

(1) (42) (43) (46) (47) (53) (67) (80) (81) (82)
(83) (84) (114) (128) (129) (153) (162) (168) (169) (171)
(174) (180) (189) (190) (191) (192) (193) (213) (221) (227)
(241) (253) (255) (260) (264) (266) (267) (307) (330) (360)
(377) (397) (402) (411) (421) (437)

Flow in Restrictors

(19) (57) (70) (95) (98) (130) (134) (147) (155) (164)
(165) (168) (170) (178) (179) (186) (190) (197) (198) (212)
(218) (225) (258) (268) (276) (285) (286) (294) (300) (304)
(309) (311) (312) (321) (322) (334) (337) (340) (344) (354)
(360) (365) (367) (368) (369) (370) (372) (373) (375) (390)
(391) (395) (397) (437) (438) (444) (445) (452) (456) (464)

Self-Acting Bearings Analysis, General

(21) (32) (33) (35) (52) (76) (78) (85) (94) (99)
(100) (101) (102) (103) (104) (108) (110) (111) (112) (113)
(132) (133) (135) (136) (138) (155) (199) (200) (201) (202)
(203) (204) (205) (206) (207) (208) (215) (219) (220) (245)

(247) (256) (257) (259) (290) (297) (302) (313) (314) (323)
(324) (325) (342) (343) (375) (384) (398) (401) (404) (405)
(406) (407) (409) (413) (418) (419) (420) (422) (424) (426)
(427) (434) (447) (462)

Self-Acting Journal Bearings of Finite Width

(23) (24) (25) (26) (27) (28) (30) (34) (35) (54)
(59) (62) (63) (66) (71) (77) (92) (93) (118) (126)
(133) (1a3) (137) (138) (139) (143) (145) (151) (158) (166)
(183) (204) (205) (206) (207) (208) (219) (248) (252) (278)
(279) (314) (324) (325) (343) (378) (385) (394) (398) (400)
(401) (403) (405) (406) (407) (408) (409) (413) (418) (426)
(445) (447) (453) (455) (462)

Self-Acting Journal Bearings of Infinite Width

(29) (31) (52) (62) (76) (93) (99) (100) (101) (109)
(110) (135) (201) (202) (203) (215) (223) (245) (297) (319)
(350) (373) (387) (385) (432) (454)

Self-Acting Thrust Bearings of the Pumping (Grooved) Types

(52) (58) (151) (158) (443) (445) (459)

Self-Acting Thrust Bearings of the Tilting Pad, Tapered Lane, or Discontinuous Geometry types

(12) (14) (16) (33) (38) (54) (64) (68) (102) (125)
(126) (132) (139) (141) (158) (199) (201) (206) (208) (237)
(247) (253) (257) (290) (302) (308) (310) (384) (385) (386)
(410) (419) (420) (424) (427) (434)

Materials, Coatings and Boundary Lubrication

(7) (23) (44) (45) (46) (66) (72) (73) (74) (86)
(175) (187) (252) (279) (280) (281) (283) (298) (333) (410)
(428) (432) (451)

# YEARLY INDEX

## (Year of Publication)

In this index the file numbers of reference appear under the appropriate, chronologically listed, year.

1953

(45) (46) (49)
(125) (153) (154)
(156) (182) (183)
(209) (223) (237)
(308) (374) (386)
(463)

1954

(18) (19) (50)
(67) (71) (104)
(117) (195) (196)
(273) (332) (368)
(369) (425) (428)
(438) (451)

1955

(99) (100) (102)
(103) (105) (107)
(142) (146) (213)
(321) (328) (345)
(350) (362) (363)
(364) (366)

1956

(7) (8) (48)
(51) (63) (69)
(101) (106) (108)
(109) (110) (114)
(157) (175) (186)
(198) (231) (288)
(292) (293) (298)
(301) (316) (376)
(440) (448) (453)

1957

(29) (30) (31)
(60) (70) (88)
(90) (93) (95)
(97) (116) (141)
(145) (149) (197)
(211) (212) (22))
(230) (232) (238)
(258) (340) (341)
(347) (349) (354)
(357) (361) (365)
(379) (392) (422)
(423) (450) (454)
(464)

1958

(3) (15) (20)
(120) (131) (132)
(143) (148) (152)
(155) (164) (166)
(200) (201) (202)
(239) (246) (274)
(275) (302) (319)
(346) (348) (351)
(352) (353) (387)
(400) (405) (414)
(433) (444) (455)
(460)

1959

(9) (10) (23)
(24) (32) (57)
(62) (68) (76)
(89) (92) (94)
(111) (112) (126)
(127) (135) (144)
(147) (158) (161)
(167) (168) (170)
(171) (180) (194)
(199) (203) (204)
(206) (219) (220)
(229) (234) (241)
(244) (247) (253)
(255) (256) (260)
(269) (279) (280)
(287) (290) (294)
(299) (312) (325)
(326) (327) (342)
(355) (375) (380)
(394) (396) (398)
(401) (409) (412)
(418) (419) (426)
(445) (447)

1960

(4) (25) (26)
(27) (34) (36)
(38) (44) (64)
(72) (73) (77)
(78) (85) (86)
(113) (124) (136)
(137) (139) (159)
(169) (172) (174)
(176) (177) (178)
(179) (187) (188)
(205) (207) (216)
(225) (226) 236)
(252) (261) (262)
(270) (278) (281)
(282) (283) (284)
(289) (309) (311)
(313) (320) (323)
(359) (388) (406)
(407). (420) (461)
(462)

1961

(5) (6) (14)
(16) (17) (22)
(28) (33) (35)
(39) (54) (58)
(59) (74) (79)
(91) (134) (138)
(140) (151) (173)
(208) (214) (235)
(259) (263) (264)
(265) (266) (267)
(271) (272) (276)
(277) (285) (286)
(300) (310) (322)
(324) (335) (343)
(356) (377) (395)
(402) (403) (404)
(408) (427) (429)
(434) (446)

## CORPORATE NAME INDEX

This is an alphabetical listing of the sources of the various references of the bibliography.

Escher-Wyss, Ltd.
Switzerland

(278)

Ford Motor Co.

(120) (238) (239)

Franklin Inst. Res/ Develop.

(76) (85) (88) (132)
(133) (134) (135) (136)
(139) (140) (149) (155)
(214) (269) (271) (272)
(274) (354) (379) (380)

Garrett Corp.

(236)

General Electric Company

(137) (138) (229) (235)
(254) (323) (324) (343)
(406) (407) (408) (409)

General Motors

(36)

Guggenheim Aeronautical Lab., Cal.

(311)

International Business Machines

(687) (199) (200) (201)
(202) (203) (204) (205)
(211) (259) (290)

Jet Propulsion Lab., Pasadena, Cal.

(91) (131) (162) (163)
(164) (165) (166) (167)
(168) (169) (170) (171)
(174) (178) (179) (180)
(261)

Kearfott Co., Inc.

(23) (24) (25) (26)
(27) (28)

Laboratory for Electronics, Inc.

(16)

L. C. Miller Co., Los Angeles, Cal.

(9)

Lockheed, Santa Cruz

(377)

Material Laboratory, Brooklyn 1, N.Y.

(8)

Mechanical Engineering Research Labs.
Glasgow, Scotland

(194) (460)

Minneapolis-Honeywell

(187) (252)

National Aeronautics Space Admin.

(72) (73) (332) (357)

National Bureau of Standards

(40) (234) (395)

National Gas Turbine Establishment

(389) (390) (391)

National Research Corp.

(222)

Naval Research Laboratory

(13)

Naval Shipyard, Materials Lab, N.Y.

(376)

New Britain Machine Co.

(44)

North American Aviation

(350) (437)

Pratt and Whitney

(11)

Royal Aircraft Establishment

(55) (65) (295)

Ruston and Hornsby, Ltd.

(358)

Sloan Labs., MIT

(268) (340) (345) (346)

Southern Research Institute

(173)

Sperry Gyroscope Co.

(127)

Stratos, Div. of Fairchild Corp.

(172)

Tribo Netics Labs

(280) (281) (282) (283)
(284) (285) (286)

United Kingdom Atomic Energy Authority

(63)

Wisconsin University, Chem. Lab.

(226) (359)

Wright Air Development Division

(52) (279)

## PATENTS

In this index patents of interest are tabulated in numerical order. The country of issue is the United States unless otherwise noted.

| PATENT NO. | ABSTRACT NO. | YEAR | PATENTEES | TITLE |
|---|---|---|---|---|
| RE 20 305** | 250 | 1937 | Klahn, E. | "Apparatus for Minimizing Friction and Vibration of Rotor Elements" |
| 466 645 | 457 | 1892 | Wood, W. H. | "Counter Balance for Journals" |
| 548 363* | 115 | 1942 | Crewdson, E. | "Improvements in and Relating to Bearings or Journals" |
| 685 871* | 184 | 1952 | Gerard, P. | "Improvement in Fluid Bearings" |
| 745 400 | 441 | 1904 | Westinghouse, G. | "Vertical Fluid Pressure Turbine" |
| 796 926* | 299 | 1959 | Montgomery, A. F. Sterry | "Gas Lubricated Bearings" |
| 816 330 | 240 | 1906 | Johnston, T. J. | "Frictionless Bearing for Electric Motors" |
| 856 516* | 236 | 1960 | Garrett Corp. | "Improvements Relating to Lubrication Systems" |
| 856 543* | 44 | 1960 | The New Britain Machine Co. | "Bearing Means for Supporting Machine Elements" |
| 867 600* | 235 | 1961 | General Electric Co. | "Improvements in the Rotor and Stator Construction of Gas Turbine Engines" |
| 869 200* | 151 | 1961 | Frost, A. | "Improvements in and Relating to Gas Bearings" |
| 873 202* | 446 | 1961 | Whitley, S. | "Improvements in or Relating to Gas-Lubricated Journal Bearings" |

*Issued by Great Britain.
**Reissue of U. S. Patent 2 054 055.

| PATENT NO. | ABSTRACT NO. | YEAR | PATENTEES | TITLE |
|---|---|---|---|---|
| 873 412* | 58 | 1961 | Bray, K. A.<br>W. McNocher | "Gas Bearings" |
| 915 549 | 75 | 1909 | Budd, A. V. | "Rotary Engine" |
| 930 851 | 118 | 1909 | De Ferranti, S. Z. | "Air Bearing for High Speeds" |
| 947 392 | 243 | 1910 | Junggren, O. | "Combined Thrust and Guide Bearing" |
| 1 030 153 | 37 | 1912 | Barbezat, A. | "Device to Balance Thrust in Turbines" |
| 1 067 727 | 150 | 1913 | Frederickson, J. | "Bearing for Car-Axle" |
| 1 070 088 | 431 | 1913 | Van Deventer, J.H. | "Counterbalanced Bearing" |
| 1 185 571 | 2 | 1916 | Abbott, W. G. | "Device for Utilizing Fluid Under Pressure for Lubricating Relatively Movable Elements. |
| 1 337 742 | 1 | 1920 | Abbott, W. G. | "Gas-Lubricated Bearing" |
| 1 385 423 | 47 | 1921 | Bibbins, R. E. | "Compass" |
| 1 629 577 | 251 | 1927 | Klahn, E. | "Art of Sustaining Bodies in Space" |
| 1 893 995 | 242 | 1933 | Jung, K. | "Bearing for Accurately Running Shafts Using Ball Bearings" |
| 1 906 715 | 329 | 1933 | Penick, E. R. | "Air Bearing" |
| 2 054 055 | 250 | 1937 | Klahn, E. | "Apparatus for Minimizing Friction and Vibration of Rotor Elements" |
| 2 068 458 | 296 | 1937 | Moller, W. | "Bearing" |
| 2 086 896 | 80 | 1937 | Carter, L. F. | "Air Supported Gyroscope" |
| 2 086 897 | 81 | 1937 | Carter, L. F. | "Air Borne Artificial Horizon" |
| 2 086 898 | 82 | 1937 | Carter, L.F. | "Air Borne Directional Gyroscope" |
| 2 095 313 | 83 | 1937 | Carter, L. F.<br>W. Bolster | "Air Borne Gyroscope" |

| PATENT NO. | ABSTRACT NO. | YEAR | PATENTEES | TITLE |
|---|---|---|---|---|
| 2 113 335 | 435 | 1938 | Wallgren, A.G.F. | "Bearing" |
| 2 133 809 | 84 | 1938 | Carter, L. F.<br>W. Anscott | "Gyrovertical" |
| 2 177 053 | 56 | 1939 | Boyd, G. A. | "Oil Burner" |
| 2 200 976 | 42 | 1940 | Bates, M.F. | "Resetting Means for Air Borne Gyroscope" |
| 2 262 232 | 53 | 1941 | Bolster, W. | "Multiple Gyro Air Borne Compass" |
| 2 449 297 | 227 | 1948 | Hoffer, F. W. | "Automatic Fluid Pressure Balancing System" |
| 2 474 072 | 411 | 1949 | Stoner, G. H. | "Air Bearing Gyroscope" |
| 2 502 173 | 333 | 1950 | Potts, L.D. | "Fluid Balancing Means" |
| 2 511 543 | 339 | 1950 | Rawlins, J. A. | "Gas Lubricated Bearing" |
| 2 523 310 | 249 | 1950 | Kirkpatrick, J. | "Hydraulic Thrust Bearing" |
| 2 535 454 | 338 | 1950 | Rawlins, J. A. | "Air Lubricated Thrust Bearing" |
| 2 544 720 | 318 | 1951 | Ospina-Racinas,E. | "Pneumatic Toy" |
| 2 597 371 | 330 | 1952 | Perkins, G. S.<br>P. R. Vogt<br>R. R. Weber | "Double Ended Journal Air Bearing" |
| 2 602 632 | 381 | 1952 | Serduke, J. J.<br>R. O. Webster | "High Speed Bearing and Turbine" |
| 2 603 539 | 61 | 1952 | Brewster, O. C. | "High Speed Rotor Using Gas-Lubricated Bearings to Get Away From Whip" |
| 2 605 147 | 334 | 1952 | Raichle, L. | "Thrust Balancing for Vertical Shafts" |
| 2 617 695 | 397 | 1952 | Slater, J. M.<br>V. A. Tauscher | "Zonal Ball-Air Bearing" |
| 2 617 696 | 228 | 1952 | Honess, W. T. | "Air Bearing Thrust and Radial Supporting Bearing" |

| PATENT NO. | ABSTRACT NO. | YEAR | PATENTEES | TITLE |
|---|---|---|---|---|
| 2 623 353 | 181 | 1952 | Gerard, P. L. | "Combined Fluid Bearing and Mechanical Bearing for Gas Turbing Engines." |
| 2 627 443 | 45 | 1953 | Becker, H. I. | "Air Bearing Graphite Lining (Porous)." |
| 2 634 176 | 183 | 1953 | Gerard, P. L. | "Fluid Pressure Bearing." |
| 2 644 727 | 421 | 1953 | Tauscher, V. A.<br>J. M. Slater<br>J. Emmi | "Double Ball Gyro Precession Axis Bearing. |
| 2 645 534 | 46 | 1953 | Becker, H. I. | "Air Bearing Graphite Lining (Porous)." |
| 2 660 484 | 182 | 1953 | Gerard, P. L.<br>H. Seranne | "Fluid Bearing." |
| 2 671 700 | 382 | 1954 | Seyffert, M. | "Air Bearing Apparatus." |
| 2 683 635 | 451 | 1954 | Wilcox, R. M. | "Air Bearing." |
| 2 684 272 | 19 | 1954 | Annen, R. | "Fluid Support Bearing." |
| 2 695 198 | 67 | 1954 | Brugger, R. G. | "Air Bearing." |
| 2 695 199 | 50 | 1954 | Blizard, R. B. | "Bearing." |
| 2 696 410 | 428 | 1954 | Topanelian, E.Jr. | "Journal Bearing." |
| 2 707 355 | 328 | 1955 | Peiler, K. E. | "Sting-out Baffle for Glass Feeder Rotor Bearing. |
| 2 710 234 | 213 | 1955 | Hansen, S. | "Fluid Bearing Mount." |
| 2 734 318 | 316 | 1956 | Offen, A. | "Laps." |
| 2 738 238 | 293 | 1956 | Michelson, H. | "Bearings." |
| 2 752 197 | 288 | 1956 | Marco, S. M. | "Rotary Nozzle for Soot Blowers and the Like." |
| 2 754 641 | 48 | 1956 | Bidwell, E. C. | "Work Holding and Clamping Mechanism for Centerless Grinding Machines. |

| PATENT NO. | ABSTRACT NO. | YEAR | PATENTEES | TITLE |
|---|---|---|---|---|
| 2 756 114 | 69 | 1956 | Brunzel, N. | "Pressure Lubricating Bearing." |
| 2 756 115 | 292 | 1956 | Michel, R. O. | "Pneumatic Bearing Construction." |
| 2 868 593 | 241 | 1959 | Jones, E. M. | "Rotary Air Bearing." |
| 2 879 111 | 220 | 1959 | Heinrich, G. A. Slibar | "Gas Lubricated Radial Journal Bearings." |
| 2 916 332 | 327 | 1959 | Pavlecka, V. | "Aerostatic Bearings with Fluid-Dynamic Seals." |

## PREVIOUS TECHNICAL REPORTS

Contract Nonr-2342(00), Task Nr 097-343, sponsored jointly at The Franklin Institute Laboratories by the Department of Defense, Atomic Energy Commission, Maritime Administration and the National Aeronautics and Space Administration. Administered by the Office of Naval Research, Department of the Navy.

Technical Project Reports

I-A2049-1 A Bibliography on Gas-Lubricated Bearings, by E. B. Sciulli, 12/1/57.

I-A2049-2 The Influence of the Molecular Mean Free Path on the Performance of Hydrodynamic Gas-Lubricated Bearings, by A. Burgdorfer, March, 1959.

I-A2049-3 Annual Report ONR Project A2049, by D. D. Fuller, 7/15/58.

I-A2049-4 A study of the Stability of Externally-Pressurized Gas Bearings, L. Licht and H. G. Elrod, November 1958.

I-A2049-5 A Derivation of the Basic Equation for Hydrodynamic Lubrication with a Fluid Having Constant Properties, By H. G. Elrod, April 1959.

I-A2049-6 A Bibliography on Gas Lubricated Bearings-Revised, by E. B. Sciulli, 9/15/59.

I-2049-7 Axial Relative Motion of a Circular Step Bearing, by L. Licht, October 1959.

I-2049-8 Stability of Externally-Pressurized Gas Journal Bearings, by L. Licht, October 1959.

Technical Project Reports

I-A2049-9 Extension of the Conducting Sheet Analogy to Externally-Pressurized Gas Bearings, by L. Licht, October 1959.

I-A2049-10 Refinements of the Theory of the Infinitely Long, Self-Acting Gas-Lubricated Journal Bearings, by H. G. Elrod and A. Burgdorfer, January 1960.

I-A2049-11 Perturbation Analysis of the Stability of Self-Acting, Gas-Lubricated Journal Bearing, by V. Castelli and H. G. Elrod, February 1960.

I-A2049-12 A Theoretical and Experimental Study of Externally-Pressurized Gas Bearings, by L. Licht, February 1961.

I-A2049-13 Theory and Design Data for Continuous-Film Self-Acting Journal Bearings of Finite Length, by H. G. Elrod, Jr., and S. B. Malanoski, November 1960.

I-A2049-14 Interim Report on the Development of Gas-Lubricated Bearings for Closed-Cycle Gas-Turbine Rotors, by M. W. Eusepi and D. D. Fuller, June 1961.

I-A2049-15 The Theory of Pulsating Flow in Conical Nozzles, by H. G. Elrod, Jr., February 1961.